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13. ABSTRACT (Maximum 200 words)

THE PURPOSES OF THIS STUDY WERE TO ACCOMPLISH THE FOLLOWING TASKS WITH THE BANA (BASIN A NECK AREA): 1.) QUANTIFY THE GROUND WATER FLOW REGIME AT THE "NECK" OF BASIN A FOR FLOW EXITING BASIN A TO THE NORTHWEST, 2.) QUANTIFY THE DISTRIBUTION OF VARIOUS POLLUTANTS IN THE GROUND WATER FLOW SYSTEM EXITING BASIN A TO THE NORTHWEST, 3.) IDENTIFY ANY OTHER GROUND WATER FLOW PATHS (BESIDES THE EXIT FLOW TO THE NORTHWEST (IN THE ALLUVIAL AQUIFER) LEAVING BASIN A, 4.) TO DETERMINE THE AREAS OF SIGNIFICANT MOVEMENT FOR POLLUTANTS IN THE GROUND WATER FLOW EXITING BASIN A. THIS REPORT PRESENTS THE FINDINGS OF THE ABOVE TASKS PERFORMED BY WES. THE RESULTS OF PHYSICAL LABORATORY TESTS ON "UNDISTURBED" SAMPLES ARE INCOMPLETE, AND WILL BE PUBLISHED AS AN ADDENDUM TO THIS REPORT.

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HYDROGEOLOGY AND WATER QUALITY OF BASIN A NECK AREA
ROCKY MOUNTAIN ARSENAL, DENVER, COLORADO

by

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Prepared for

Rocky Mountain Arsenal
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and
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Aberdeen Proving Ground, Maryland

PREFACE

This investigation was conducted during the period October 1978 through July 1979 by personnel of the Engineering Geology and Rock Mechanics Division (EGRMD), Geotechnical Laboratory (GL), and Environmental Engineering Division (EED), Environmental Laboratory (EL), of the U. S. Army Engineer Waterways Experiment Station (WES). The study was authorized by Intra-Army Order for reimbursable services No. RM 53-79 dated 29 September 1978.

This report was prepared by Messrs. F. Bopp, III, Engineering Geology Applications Group (EGAG), EGRMD, and J. R. Kolmer, Treatment Processes Research Branch (TPRB), EED. The report was prepared under the direct supervision of Messrs. J. H. Shamburger, Chief, EGAG, EGRMD, and N. R. Francingues, Jr., Chief, TPRB, and under the general supervision of Dr. D. C. Banks, Chief, EGRMD, Messrs. A. J. Green, Jr., Chief, EED, and J. P. Sale, Chief, GL, and Dr. J. Harrison, Chief, EL.

Special acknowledgment is extended to the following individuals for their assistance and review of findings: Messrs. Ed Berry, Irvin Glassman, Don Cook, Brian Anderson, Greg Ward, and Carl Loven of Rocky Mountain Arsenal; and Messrs. Andrew Anderson, James Zarzycki, and Don Campbell, U. S. Army Toxic and Hazardous Materials Agency, Aberdeen Proving Ground, MD.

Commanders and Directors of WES during the preparation of this report were COL John L. Cannon, CE, and COL Nelson P. Conover, CE. Technical Director was Mr. F. R. Brown.

CONTENTS

HYDROGEOLOGY AND WATER QUALITY OF BASIN A NECK AREA
ROCKY MOUNTAIN ARSENAL, DENVER, COLORADO

PART I: INTRODUCTION

Background

1. Basin A Neck Area (BANA) is defined as the area bounded on the southeast by Basin B and cross section line F-F', on the south by a line connecting boring No. 657 with boring No. 639, on the west by a line connecting boring Nos. 639 and 378, and on the north by 9th Avenue between boring Nos. 356 and 378 and on the east by a line between boring Nos. 378 and 130 (see Figure 1). This area encompasses Basins C, D, E, and F.

2. Although not identified as a separate entity in the original Rocky Mountain Arsenal (RMA) Contamination Survey Plan,* this area was identified as a study area to determine what course(s) the groundwater takes after exiting Basin A. The objective and approach to the BANA was the same as those authorized for Basin A in the RMA Contamination Survey Plan and the memorandum of understanding among RMA, U. S. Army Engineer Waterways Experiment Station (WES), and U. S. Toxic and Hazardous Materials Agency (USATHMA), dated 26 July 1978.**

3. In response to the memorandum of understanding, an implementation and test plan for BANA was submitted to and approved by RMA and USATHMA. In addition, a sampling and analysis program for water quality for Basin A and BANA was prepared. Work was initiated in this project in October 1978.

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* DRCPM (now USATHAMA)-DRR letter dated 13 July 1979, with inclosure, Subject: Rocky Mountain Arsenal (RMA) Contamination Survey Plan.

** DRCPM-DRR letter dated 2 August 1978, with inclosure, Subject: Memorandum of Understanding, Rocky Mountain Arsenal (RMA) Contamination Survey.

Purpose and Scope

4. The purposes of this study were to accomplish the following tasks within the BANA:

a. Quantify the groundwater flow regime at the "neck" of Basin A for flow exiting Basin A to the northwest.

b. Quantify the distribution of various pollutants in the groundwater flow system exiting Basin A to the northwest.

c. Identify any other groundwater flow paths (besides the exit flow to the northwest [in the alluvial aquifer (ALL)]) leaving Basin A.

d. Determine the areas of significant movement for pollutants in the groundwater flow exiting Basin A.

5. This report presents the findings of the above tasks performed by WES. The results of physical laboratory tests on "undisturbed" samples are incomplete, and will be published as an addendum to this report.

PART II: FIELD DATA COLLECTION

Exploratory Drilling and Piezometer Installation

6. Tentative locations were selected for drilling 23 exploratory borings and listed in the implementation and test plan,* with the option of additional borings in the area if required. Each boring extended to 100 ft or less, to assist in determining the hydrogeologic characteristics of the area. Split-spoon samples were obtained at 5-ft intervals or at stratum changes, whichever was more frequent. Upon completion of each boring, the exploratory hole was backfilled with grout. If a dry hole was encountered it was backfilled from the cuttings. Where water was found in one or more of the strata in an exploratory boring, observation wells were installed in each water bearing strata to be used as piezometers, for rising head or falling head tests and for water quality sampling. An observation well for each of the aquifer units encountered in a boring was installed at a distance of about 5 ft from the exploratory boring. Undisturbed samples of each aquifer unit were collected. An observation well consisted of a 2-in. slotted PVC screen that extended the entire thickness of the aquifer unit and attached to an unslotted 2-in. PVC pipe that extended 2 ft above the ground surface. A pea gravel or sand packing was emplaced around the entire screen and the aquifer sealed with a bentonite and portland cement grout barrier placed above the screen. The remaining hole was backfilled with grout. Each well was flushed with as small a volume of water as possible to clear the screen packing, without adding a significant amount of diluent to any contaminated groundwater which may be present.

7. Exploratory borings and piezometer placements were accomplished at the original 23 sites plus 6 additional discretionary sites. Plate 1

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* WESGV letter dated 13 September 1978 with Incl 1, Subject: Basin A Neck Area, Implementation and Test Plan, Rocky Mountain Arsenal (RMA) Contamination Survey.

identifies the locations of all borings in the BANA. Borings accomplished for this task are numbered 801-826 inclusive plus 640, 651, and 455. Twenty-one observation wells ~~(or piezometers)~~ were installed in the ALL, while 15 sealed piezometers were installed in the upper Denver sand (UDS), and 13 sealed piezometers were installed in the lower Denver sand (LDS). Table 1 is a summary of all boring data obtained under BANA tasks.

Water Level Measurements

8. Water level measurements were taken using a conventional "M-scope," a battery-powered electrical probe which uses the slight electrical conductivity of water to sense the water surface. The "M-scope" probe was lowered slowly down the casing of each of the satellite borings, while monitoring the needle of an electrical conductivity meter wired in parallel across the probe. As long as the probe remains in air the electrical conductivity remains negligible (resistivity of air being virtually infinite). Immediately upon contact of the probe with the water surface within the casing, the needle displaying electrical conductivity on the meter shows a marked deflection (increase in conductivity, decrease in resistivity to finite values). By maneuvering the probe up and down across the air-water interface, the actual contact point of the probe with the interface can be identified with a relatively high degree of accuracy. The distance between the top of casing and the air-water interface was read from calibration marks on the wire connecting the probe to the meter. The elevation of the water surface (piezometric surface) was determined by subtracting this measured distance from the surveyed elevation of the top of casing. Although these measurements are usually accurate, with proper exercise of caution, within ±0.05 ft, the measurements were usually reported to the nearest 0.1 ft.

9. Initial water level measurements were made prior to well development. Since several of these measurements differed substantially from readings taken subsequent to well development these readings were

not used in interpretation. After well development, water levels were routinely measured prior to initiation of standard sampling procedures described below.

Water Quality Sampling

10. Each well was developed and used to obtain samples for water quality analysis. The methods used for sampling have been standardized for WES participation on RMA projects. The procedure is as follows:

a. Measure depth from top of casing to top of water. Record depth for future use in development of groundwater contour map.

b. Measure depth from top of casing to bottom of well casing (total depth of cased hole) for initial sampling of new installation or use previously recorded depth for resampling of established installation.

c. Subtract depth to top of water from depth to bottom of casing to determine the height of standing water in the casing.

d. For every foot of standing water:
(1) Remove 1.5 gal of water, if well is pumped, or
(2) Remove 3 bailer volumes (5-ft bailer), if well is bailed.

e. If well goes dry before pumping or bailing is complete, allow the well to recover and again empty the well.

f. Immediately recover a sample for chemical analysis after pumping or bailing is complete (Step d). In case a well is pumped or bailed dry, recover a groundwater sample as soon as possible while the well is recovering the second time.

11. Water quality samples were recovered in accordance with the standard procedure and submitted to RMA, Material Analysis Laboratory Division (MALD), for routine chemical analyses. The samples recovered for this study were analyzed for aldrin, chloride, O-sulfone, O-sulfoxide,

nemagon (DBCP), dicyclopentadiene (DCPD), diisopropylmethylphosphonate (DIMP), dithiane, dieldrin, endrin, fluoride, isodrin, oxathiane, and O-sulfide.

Slug Tests

12. Slug tests were conducted on 29 of the borings to determine the coefficient of permeability of strata at depths of the slotted sections of PVC pipe. In a slug test the water level in a well is lowered essentially instantaneously by rapidly removing a fixed volume of water with a bailer followed by observation of the change in water level with time. For each slug test the change in water level, as determined from the response of a pressure transducer, was recorded on an oscillograph recorder.

13. Slug tests were performed four times on the UDS sealed piezometer at site 455 with all four results lying within a 2.2 percent spread. All tests were performed, and data reduced (as described in Broughton et al., 1979 and Basin F draft report, 1979).

14. A total of 39 field slug tests were performed. Six tests which overlap with the Basin A study and four which overlap with the deep drilling assessment around Basin F were used in this study. All of these data are presented in Table 2. Nine tests were conducted in the ALL but due to the extreme desaturation of the ALL, falling head tests were required—type curve matching was poor on these tests, and the permeability values obtained should be considered to be questionable.

Physical Testing

15. Undisturbed samples taken from 30 of the borings at the depths of the PVC screened intervals were returned to WES, X-rayed to determine soil structural features, and delivered to personnel of the Soils Testing Facility, Geotechnical Laboratory, to determine the natural water content, dry density, grain size distribution (for classification

purposes), and laboratory determination of the coefficient of permeability. Test methods employed were in general accordance with the Corps of Engineers Manual for Laboratory Soils Testing (EM 1110-2-1906, 30 November 1970).

PART III: HYDROGEOLOGY

Geologic Setting

16. The RMA is underlain by layers or lenses of clays, silts, sands, and gravels varying in aggregate thickness of up to approximately 60 ft. These soils are generally referred to as the "alluvial aquifer," "upper aquifer," or "upper alluvial materials," or "alluvium." At the base of the alluvium lies a clay shale or shale layer (termed, in the past, as the "bedrock surface"). This underlying surface is the subcrop of the Paleocene (lower Tertiary) Denver formation. The Denver formation contains sequences of clays (or clay shales), sands, siltstone and sandstone layers or lenses of variable thickness. The project borings penetrated up to two sequences of shale and sand of the Denver formation.

Top of the Denver Formation

17. Elevations of the top of the Denver formation were tabulated for approximately 175 boring sites in the BANA, Basin A, and southernmost F-to-North-Boundary area. These elevations were plotted in plan view, linear interpolation was used, and a map of Denver topography was contoured (see Plate 2). This map has as its most prominent feature a deeply incised stream channel across the neck of Basin A, and trending roughly from east to west toward the west boundary of the arsenal. During periods of high saturated thicknesses in the ALL this map would be less instructive than it is under current low-saturated thickness conditions. Plate 2 indicates that under low-saturation conditions in the ALL, alluvial water flow may become controlled by the Denver topography, in which case it is difficult to imagine any significant flow from Basin A flowing anywhere but to the west.

18. A second feature of Plate 2 is the less-prominent channel exiting Basin F to the northeast. Most alluvial flow under Basin F, including vertical leakage from Basin F, would be constrained by the

Denver topography to flow northeast across 9th Avenue before contributing to the F-to-North Boundary flow regime.

Groundwater Levels

19. As mentioned before, the ALL was in a period of very low saturated thickness conditions during the study. Water level surveys were accomplished in early January, late March, and early June, and most readings are relatively consistent over that period. Some wells showed slightly increasing saturated thicknesses (i.e., well Nos. 626-639) but most of the changes over the three surveys showed water level declines of a few tenths of a foot to over 2 ft. Many wells in all three surveys were "dry." In order to be considered as "dry" one of two conditions must be met:

a. There is no water in the well, in which case the well is quite literally "dry," or

b. The water level elevation reported from the survey is below the elevation of the top of the Denver formation in which case the well is functionally "dry."

Plate 3 is a map of water level elevations in the ALL for 1 June 1979. Linear interpolation was used between data points. Saturated thicknesses were examined, the contoured map compared with the "bedrock" topography map, Plate 2, and the "bedrock" topographic control of flow in the ALL became obvious. Areas of "dry" wells are denoted with the pattern; data control is shown with solid dots (●).

20. The most dominant feature of Plate 3 is the bifurcating pattern of alluvial flow. The steepest ALL flow gradients are to the west, coinciding with the position of the incised channel in Plate 2. The portion of this bifurcating flow which passes under Basin F is probably a minor component of total ALL flow in the BANA. Indeed, with Plate 3 contoured as shown, only flow from Basin A on the extreme northeast side of the "neck" could possibly follow the gradients shown and actually flow under Basin F. The low flow rate from Basin A, only about 0.4 gpm, probably cannot reach the underflow regime around Basin F, under current low ALL flow conditions.

21. Plate 4 is a contour map of water level elevations for the UDS. Data control, as shown by the solid dots, is sparser than for the ALL map, but is still well enough distributed to result in reasonable confidence in the map. Flow paths in the UDS are generally to the northwest, and they are broadly similar in pattern and distribution to the water level contours in the ALL, Plate 3. The general similarity in contour shape between the ALL and the UDS indicates the possibility of hydraulic interconnection between these two aquifers. In most areas the ALL heads range from about 1 ft to as much as 10 ft higher than heads in the UDS. Areas in which the ALL and UDS heads are quite similar are on the northeast side of the neck of Basin A and the southeastern corner of Basin F, suggesting "windows" of interconnection in both areas. Boring logs from Basin A (Broughton et al., 1979) confirm a "window" in the neck of Basin A, and boring logs for sites 444, 448, 452, 455, 456, 876, 877, and 883 (these last three are exploratory borings done by Earth Sciences Associates, architectural engineer contractor to Black & Veatch) confirm the presence of a "window" at the southeastern corner of Basin F.

22. Plate 5 is a contour map of water level elevations for the LDS. Data control, as shown by the solid dots, is even sparser than for the UDS. Without additional data control Plate 5 should be used with caution. LDS contours are broadly similar to both the ALL and UDS maps, Plates 3 and 4. However, heads in the LDS are generally from about 5 ft to more than 25 ft lower than heads in the UDS. Areas in which UDS and LDS heads are quite similar (within about 3 ft of each other) are at site 809 where a UDS-LDS "window" is documented by the boring log, and along the southwestern half of line F-F' where a UDS-LDS window has been inferred from boring logs. Contours are also quite similar along the western side of Basin F, suggesting a window in that area, although data control is too sparse to have any confidence in a conclusion based upon that suggestion. Other interesting patterns to note are: (a) the northeasterly flow path in the neck of Basin A, (b) the axis of westerly flow which is apparently located approximately 1000 ft further south in the LDS than in the UDS and is oriented approximately 45 deg southwest from the axis of UDS westerly flow, (c) the virtually perpendicular

orientation of UDS versus LDS flow lines in the neck of Basin A, and (d) heads in the LDS are higher than those in the UDS in the neck of Basin A between section lines F-F' and G-G'.*

23. Plates 6 through 12 present stratigraphic cross sections for section lines F-F', and for lines U-U' through Z-Z', as shown on Plate 1. The heavy line of highest elevation on each plate is the ground surface elevation. The next heavy line at a lower elevation is the top of the Denver Formation. The heavy line of lowest elevation divides the upper part of the Denver Formation containing the UDS from the lower part of the Denver Formation containing the LDS. Whether this line represents an erosional unconformity, a redox boundary, a facies boundary, or some other phenomenon is still subject to speculative interpretation. In the upper Denver very little lignite is present in the clays, clays usually show evidence of oxidation (small stringers of limonite and hematite) and the UDS is generally a yellow to orange-yellow to green-yellow slightly silty sand (SM) in the Unified Soil Classification System (USCS)). Below this line lignite is abundant, there is no evidence of oxidation of iron, and the LDS is usually a pale-gray to blue-gray fine, SM. This evidence tends to support the idea that the third heavy line is a redox boundary dividing an oxidized UDS zone from a reduced LDS zone. Inferred correlations are indicated by dashed lines, while correlations from adjacent holes are shown with solid lines. Positions of all well screens are shown on Plates 6 through 12 with a horizontal pattern. Total depth of penetration is shown by the vertical lines beneath the boring locations indicated with arrows and boring numbers.

24. Several observations are possible from these cross sections concerning the interconnectivity of the ALL and UDS aquifer are:

a. Section F-F'.

(1) The ALL is in direct contact with the UDS between boring Nos. 723 and 648.

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* WESGR letter dated 2 August 1978, with inclosure, Subject: Basin A Neck Area, Implementation and Test Plan, Rocky Mountain Arsenal (RMA) Contamination Survey.

(2) The UDS is inferred to be in direct contact with the LDS between boring Nos. 650 and 651.

(3) Only the deep screens at boring Nos. 651 LDS, 640 UDS, and 723 through 725 are known to have been sealed with grout, leaving the possibility of drilling-induced contamination migration at many of the other screens in the Denver formation.

b. Section U-U'.

(1) A window between ALL and UDS is strongly suggested between boring Nos. 817 and 818, and redrilling boring No. 139 could help confirm this suggestion. Since the ALL was "dry" in this area during this study, cross contamination is probably not an immediate problem.

c. Section V-V'.

(1) A man-made ALL-UDS window is possible at boring No. 141 where the confining CH (highly plastic clay in the USCS) at the top of the Denver formation is only about 3 ft thick. The exploratory drilling completely penetrated this CH and a gravel-packed trap enters the UDS here.

(2) A natural ALL-UDS window was drilled through at site 813. The inferred dimension of this window is approximately 600 ft along V-V'.

(3) A UDS-LDS window is possible and inferred between boring Nos. 815 and 675.

d. Section X-X'.

(1) An ALL-UDS window was drilled through at site 803. Its lateral extent is inferred at approximately 1300 ft in the vicinity of 803.

(2) A UDS-LDS window was drilled through at site 770 (Broughton et al., 1979). Its lateral extent is inferred at about 1000 ft near 770.

e. Section Y-Y'.

(1) An ALL-UDS window was drilled through by all exploratory borings on Y-Y' northeast of site 490. Its inferred extent is approximately 4000 ft along Y-Y'.

(2) The shallow screen at site 455 has a 67-ft trap on the bottom of the screen, and is probably gravel-packed from the ALL all the way into the LDS thereby aggravating contamination cross connections.

f. Section Z-Z'.

(1) There is an ALL-UDS window across most of the southern end of Basin F between boring Nos. 805 and 456. Its lateral extent is inferred to be about 2200 ft along Z-Z'.

(2) A small UDS-LDS window is inferred to be between sites 492 and 804, and may be the lateral continuation of the UDS-LDS window drilled at site 809 to the south.

In addition, borings not included in the sections where windows connect the UDS and the LDS are 809, 823, and 825. At these sites the sealed piezometers are screened from the bottom of the LDS across the UDS contact and several feet higher.

Total Mass Flux

25. Four section lines were selected to cover mass flux flow components in BANA. These were: line F-F', line Y-Y', line Z-Z', and 9th Avenue across the north side of section 26. Plates 13 through 16 illustrate the saturated thicknesses of aquifer materials, either present or inferred, along each of these lines. Water levels were plotted on each of the appropriate cross sections and the saturated thickness of "coarse-grained" materials was measured. These saturated thicknesses were plotted as a function of boring location along the section. Cross-sectional areas of the saturated aquifer materials were calculated for use in the expression for calculating flux, Equation 1 below:

$$Q = K\,i\,A \tag{1}$$

where

Q = total volume flux (gal/day).

K = measured permeability (gal/day-ft^2).

i = hydraulic gradient (ft/ft).

A = cross sectional area (ft^2).

Values of A and K were substituted in the above expression along with appropriate i values as interpolated from Plates 3 through 5.

26. Prior to calculating the ALL flux, the field permeability test results in the ALL aquifer of BANA were determined to be of poor quality and would not be used. To obtain a value of K for the ALL, the results were back-calculated from the pump test of well No. 368 just north of 9th Avenue. Plate 16 shows the saturated thickness of ALL at 9th Avenue, a total cross sectional area of 16,840 sq ft. The local gradient from Plate 3 was very low, and averaged roughly 0.0006 ft/ft. The K value from the pump test of boring No. 368 was used, .33 cm/sec (7000 gpd/ft^2). Thus, the computed total volume of water in the ALL passing 9th Avenue away from Basin F is 49 gpm. On the basis of water quality work done on water from well 118 at the northeast corner of Basin F it has been shown that Basin F fluid leaking into the ALL is diluted roughly tenfold. Therefore, it was assumed that 5 gpm were leaking out of Basin F into the ALL. This is a relatively reasonable number since: (a) if one assumes a permeability for the bottom of Basin F of about 10^{-8} cm/sec (0.0002 gal/day-ft^2); (b) assumes a uniform head gradient of about 5 ft/ft driving vertical leakage; and (c) assumes an area for the basin of roughly 4×10^6 ft^2; the leakage works out to less than 10 gpm. A total volume flux was computed for the UDS at line Z-Z', where heads indicate (Plates 3 and 4) that the UDS could be discharging into the ALL beneath Basin F. This flux was computed to be about 13 gpm. This left a residual of 31 gpm (assuming the Basin F flow regime is in an equilibrium balance) which needed to be crossing line Z-Z' in the ALL. Using this flux and gradients from Plate 3, the ALL permeability in BANA was computed to be 480×10^{-4} cm/sec (1019 gal/day-ft^2). This value was used in all calculations involving the ALL aquifer in BANA.

27. Table 3 summarizes the total flux computations made for the four lines previously mentioned. As had been shown (Basin F draft report, 1979) flow out of Basin A is quite low in all three aquifers. An independent calculation here of the flux across line F-F' in the ALL was within a few percent of the flux computed by Kolmer (1979). By inspection of Plate 3 it is obvious that all ALL flow across line F-F' should also eventually cross lines Y-Y' and Z-Z'. As can be seen in Table 3, the ALL flux across both of these lines is about two orders of magnitude higher than the present ALL flux out of Basin A. Three possible explanations of this phenomenon are possible:

- a. Field permeability data, and therefore the flux calculations, are erroneous.
- b. There is a great degree of interconnection among the three aquifers, thereby rendering a water balance between Basin A and BANA too complex to compute from the available data control.
- c. There are water masses in motion at RMA which reflect different ages, and therefore, different rainfall infiltration and waste disposal rates, thereby rendering a water-balance calculation meaningless due to non-steady-state flow conditions.

The first of these explanations is probably not correct. Preliminary results from the F-North Boundary Study indicate that the slug test results very closely mimic the pump test results in the same area, and, therefore, the slug test results in BANA and Basin A are probably reliable. The second of the explanations is quite feasible, since several areas of interconnectivity among the three aquifers have already been identified from boring logs both in Basin A (Broughton et al., 1979) and in BANA. The third explanation is also feasible since there is already at least *prima facie* evidence of more than one water mass present in Basin A (Broughton et al., 1979). Probably a combination of the second and third possibilities applies, thereby rendering a mass balance computation for BANA virtually impossible regardless of drilling control.

28. Different water masses in motion in the ALL is argued for quite powerfully when comparing Table 3 with Plate 3. Plate 3, as contoured, shows a flow net which would not allow much, if any, of the present ALL flow out of Basin A to travel to the north and flow under Basin F. And yet, the northerly flow across line Y-Y' in the ALL is almost 100 times that of the flow in the ALL exiting Basin A. Flow across the westerly ALL channel of line Y-Y' is almost 250 times that of the ALL flow exiting Basin A. Even if all of the flow from all three aquifers across line F-F' were combined with all of the UDS and LDS flow across Y-Y' (analogous to all "bedrock" flow discharging into the alluvium), this total would still account for only 66.4 percent of the ALL flow in the westerly direction across line Y-Y'. Apparently the flow across both segments of line Y-Y' in the ALL represents a "slug" of old water which may have exited Basin A as much as 20 years ago when waste disposal in Basin A kept saturated flow volume high in the ALL.

Water Quality Analysis

General

29. Field sampling work for the groundwater quality study was initiated in December 1978. The samples were recovered according to the sampling schedule as given in Appendix A, Reference 4. All samples collected in one day were delivered to the MALD for preparation and analysis the same day. The procedures employed in the analysis of these samples can be obtained from RMA.

Methods of Data Analysis

30. All chemical results obtained for the study area were recorded on plan maps. These data were also plotted on geologic cross sections according to the depth from which the samples were recovered (well screen depth). Based on the cross sections, the water quality data were correlated and segregated for the various water-bearing units within the study area. Since the contaminants exiting the Basin A study area were found to be moving in the middle water-bearing unit, the UDS, this unit were given primary emphasis in the data analysis. The correlated data

were averaged at each well screen location and plotted on plan maps. Thus, these water quality results represent a single picture in time of the distribution of the various contaminants within the study area. These averaged data were contoured and the contaminant distributions were plotted on isoconcentration maps.

Discussion of Results

31. The geology within the study area is complex, as was indicated earlier. The less permeable clay layers which function as confining beds between the various water-bearing zones were found not to be continuous over the study area. These "windows" in the confining layers provide areas where vertical water movement can occur between the various water-bearing units. While this movement may be small enough so as not to have a noticeable effect on a water balance in the study area, the effect on contaminant distribution over time could be significant. Correlation of water quality data was difficult and numerous data gaps in the control of groundwater movement, as well as water quality, were noted. The four contaminants, chloride ion, oxathiane, DIMP, and dithiane identified (Kolmer, 1979) as migrating into the BANA were closely evaluated. These were the only contaminants found in sufficient quantities to merit evaluation. The history of the disposal of these contaminants was discussed (Kolmer, 1979). The distribution of these contaminants in the UDS is shown in Plates 17 through 20. The contours close around the Basin C area, although this may be an artifact of lack of control under Basin F. The ALL in this area is dry and it is believed that the contaminant concentrations present in the UDS have resulted from vertical movement of groundwater from the ALL to the UDS.

32. Prior to 1957, during the period when Basin A was an active disposal area, there was a head on the groundwater system in the Basin A area, probably resulting from disposal activities. This head caused infiltration and groundwater flow at levels above those which would have occurred naturally. In order to accommodate this volume of contaminated groundwater there was significant flow in the ALL. Konikow's 1975 model work confirmed there was significantly more flow in the ALL during this time. When the Basin A dike was breached the quantity of infiltration

was reduced and the cross sectional area required to carry alluvial flow was also reduced. The "windows" between the ALL and the UDS acted as "drainage points" for the ALL into the UDS. In short, after use of Basin A was suspended, there was not a sufficient quantity of groundwater flow to support both the ALL and the UDS water-bearing units, and the water in the ALL moved vertically to the lower units in adjustment to the new flow quantities. Because of the "windows" between the ALL and UDS these units can in some ways be considered to be one water-bearing unit. If the quantity of groundwater flow in this combined aquifer were reduced, the water table would fall and areas that were once saturated would become desaturated and, eventually, dry.

33. The time for this reduction in saturation over the study area would vary with the distance from the source. The areas closest to the source would be affected first. Thus it is understandable that a relatively definable flow pattern from the ALL to the UDS has been established in the northern part of Basin A between the G-G' well lines and the F-F' well lines (Kolmer, 1979). As the distance from the source increased, however, the nature and extent of this vertical movement would become less definable. Further, if groundwater movement rates are slow enough, or if the UDS is not as extensive as the ALL, it would be possible to find high contaminant levels in the ALL. These levels would be representative of the trailing edge of the old pollution plume that was exiting Basin A after its period of active disposal operations. The groundwater and chemistry conditions found in the BANA study area indicate that the above described sequence of events was certainly feasible.

34. After use of Basin A was suspended the driving force and supply of groundwater flow were notably reduced. This effect moved downgradient from Basin A into the BANA. Some contaminants were carried out of Basin A with what may be looked upon as the "last flush" of pollutants from the active disposal site. These pollutants drained to the Basin C area. This "last flush" could have been a combination of both surface water and groundwater flow. If, when the Basin A dike was breached, the contained liquid was allowed to drain to Basin C, ~~and~~ was then pumped into Basin F, some of the wastes temporarily contained in

Basin C would have infiltrated to the ALL groundwater system. The driving force to move this water out of the area, however, was decreasing with time, and the contaminants probably moved both vertically and horizontally. Also, during this time, flushout of Basin A was continuing and contaminants were migrating across the F-F' well line into the study area in the UDS. This movement would have been slow, but it did help augment the contaminant levels in the UDS. If the contaminants moving vertically migrated essentially as a "slug" of highly contaminated water into the UDS, a closed contour pattern would be expected which is the pattern that has been observed in the study area. Judging by the slow rate of groundwater movement in the study area, approximately 6 cm/day (0.2 ft/day) across the F-F' line, it is feasible that this movement pattern has taken in excess of 20 years to develop, and it may take longer than that to naturally flush the upper water-bearing unit.

35. If the extent of the ALL is greater than the UDS, or if the groundwater movement rate is slow enough, it might be possible to locate the high contaminant levels in the ALL which represent the trailing edge of the contamination plumes from the original Basin A disposal activities. Plate 21 shows the distribution of chloride ion in the ALL. Comparison of Plates 18 and 21 shows that where the UDS chloride plume ends, the ALL plume is continuous with it. Further, comparison of Plates 18 and 21 with Plate 3, depicting the groundwater levels in the ALL, indicates that the contaminant distribution in the UDS matches well with the dry area in the ALL and the contaminant plumes in the ALL also correlate with the groundwater pattern shown.

36. Based on field information, the above scenario appears feasible and is compatible with known historical information as well as the data derived from the Basin A study. However, the above discussion is qualitative. A quantitative analysis will be needed to determine the fluxes and rates of movement of the contaminated flow. Because of the complexity of the BANA hydrogeology, and because placement of the piezometers (800 series borings) is relatively wide spaced, it is considered that the available information is not sufficiently well detailed to allow a strict quantitative analysis. Contaminant flux diagrams drawn

from the available information would not be considered reliable. The available data is sufficient for a good qualitative analysis, but not for quantification of contaminant movement.

PART IV: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

37. The BANA is probably the area of the RMA with the most complex geology and hydrogeology. The high degree of interconnectivity among the three aquifer units demonstrated from only 26 new borings indicates that there is probably insufficient boring control in the BANA to provide definitive stratigraphic control for adequate description of the groundwater flow regime.

38. Water quality monitoring in the BANA also indicates a complex set of interactions among the three aquifers. It would be very desirable to have well screens in many locations where they do not exist now, and further, more new boring sites and well screens would be highly desirable.

39. At present the contribution of contaminated flow from Basin A ALL to the total ALL flow in the BANA is virtually insignificant. It has probably been insignificant for at least several years, and will probably remain so at least until the front from the "mound" in the southern end of Basin A (Broughton et al., 1979) reaches the exit in the neck of Basin A.

40. With heads in the ALL higher than in the UDS, there is a high probability that contaminants in transport in the ALL are being "underdrained" into the UDS. This would make migration in the UDS much more important than heretofore suspected.

41. Chemical contamination has spread from the Basin A area into the Basin C, D, and E areas. This contamination is primarily in the UDS with the highest recorded levels in the Basin C area. It appears that this contamination may have migrated vertically from the ALL into the UDS. Rates of vertical movement versus horizontal movement, as well as the complex interrelationship of these two, are not known quantitatively.

42. The LDS showed little contamination in the study area. The deep screens in the Basin C area were the only points where some contaminants were found, but at low levels (for example, DIMP was less than

100 ppb). However, contaminants have migrated to that depth and "windows" between the UDS and LDS have been documented. In general the groundwater heads in the BANA are such that water will move progressively deeper. Thus, if "windows" between water-bearing units are in the contaminated flow path, contamination will move to the deeper water-bearing units. Vertical movement rates are not known, but are probably much slower than horizontal movement rates. Given time it is very probable that the contamination in the UDS could move to the LDS.

43. There are five main data gap areas:

a. Between Basin C and the F-F' well line, where only boring No. 658 exists, it was too shallow and no samples could be recovered.

b. The Basin C area appears to be a "hot spot" for contamination in the UDS and requires more detail to be quantified.

c. The narrow area between Basin C and Basin F. The existing wells in this area were drilled and screened in the UDS and no data is available about the ALL. These data could be significant to the interpretation and quantification of the interrelationships between the aquifers. Data obtained from these wells may be affected by water from the upper aquifer moving down around the well casing and into the lower screen. The water quality data from these wells all correlated very well for all contaminants at all depths suggesting cross contamination. None of the data could be used. This area is critical because it forms the last line of sampling before groundwater flow moves under Basin F. The lack of reliable sampling points in this area is one of the main reasons a quantitative hydrogeochemical analysis could not be done.

d. West of Basin F. The sampling points in this area are too widely scattered to allow quantitative definition.

e. Along the E-E' well line. These wells are all too shallow. Based on the available data, it appears that the UDS is

pinching out in this area, but it may just be a localized pinch-out with isolated exit areas along the E-E' line. Without deeper wells in this area, no definition is possible.

Recommendations

44. Table 4 is a listing of well screens which are recommended to be installed at existing boring sites in order to enhance geochemical control of the geohydrologic regime in the BANA. Unless rotary drilling services become available sooner, these installations should probably be postponed pending results of the geohydrologic integration study to be accomplished in Quarter 4, FY 79.

45. Table 5 is a listing of new exploratory borings and well screens in the BANA which will fill in data gaps in the geohydrologic and geochemical control presently available. These exploratory borings can be done if auger drilling services become available prior to FY 80. However, they should probably be postponed until after the recommendations of the geohydrologic integration study become available in early FY 80.

46. Inspection and plotting of a number of boring logs and screen emplacements have shown a number of installations which cross connect two or more of the aquifer units at RMA. These screen installations are probably aiding the acceleration of vertical migration of contaminants between aquifers. The only proper way of mitigating this problem is to drill out the offending screens and gravel packs and grout the holes to provide a seal between aquifers. Table 6 is a listing of such wells.

47. The physical significance of the lowest heavy lines in the stratigraphic cross sections (Plates 6 through 12) may be tested with heavy mineral analyses. If the UDS and LDS are indeed different, then their corresponding heavy numerical assemblages should show some statistically significant differences. If they are genetically related, and the heavy line is indeed a redox boundary, then the heavy mineral suites

should be quite similar. Heavy mineral analyses are recommended to be performed on not less than 10 UDS and 10 LDS samples.

48. The ages of water masses may be tested through Tritium—dating of water samples from around the arsenal. Such a dating test is highly recommended.

REFERENCES

1. Broughton, J. D., Miller, W. O., and Mitchell, G. B., "Basin A, Rocky Mountain Arsenal Contamination Survey," U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss., Draft Report, July 1979.

2. Kolmer, J. R., "Rocky Mountain Arsenal, Basin A, Groundwater Quality Analysis," U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss., Draft Report, Jul 1979.

3. U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss., "Basin F Containment Hydrogeology Assessment, Rocky Mountain Arsenal, Denver, Colorado, A Report on Results of Deep Drilling Activities, Aug 1979.

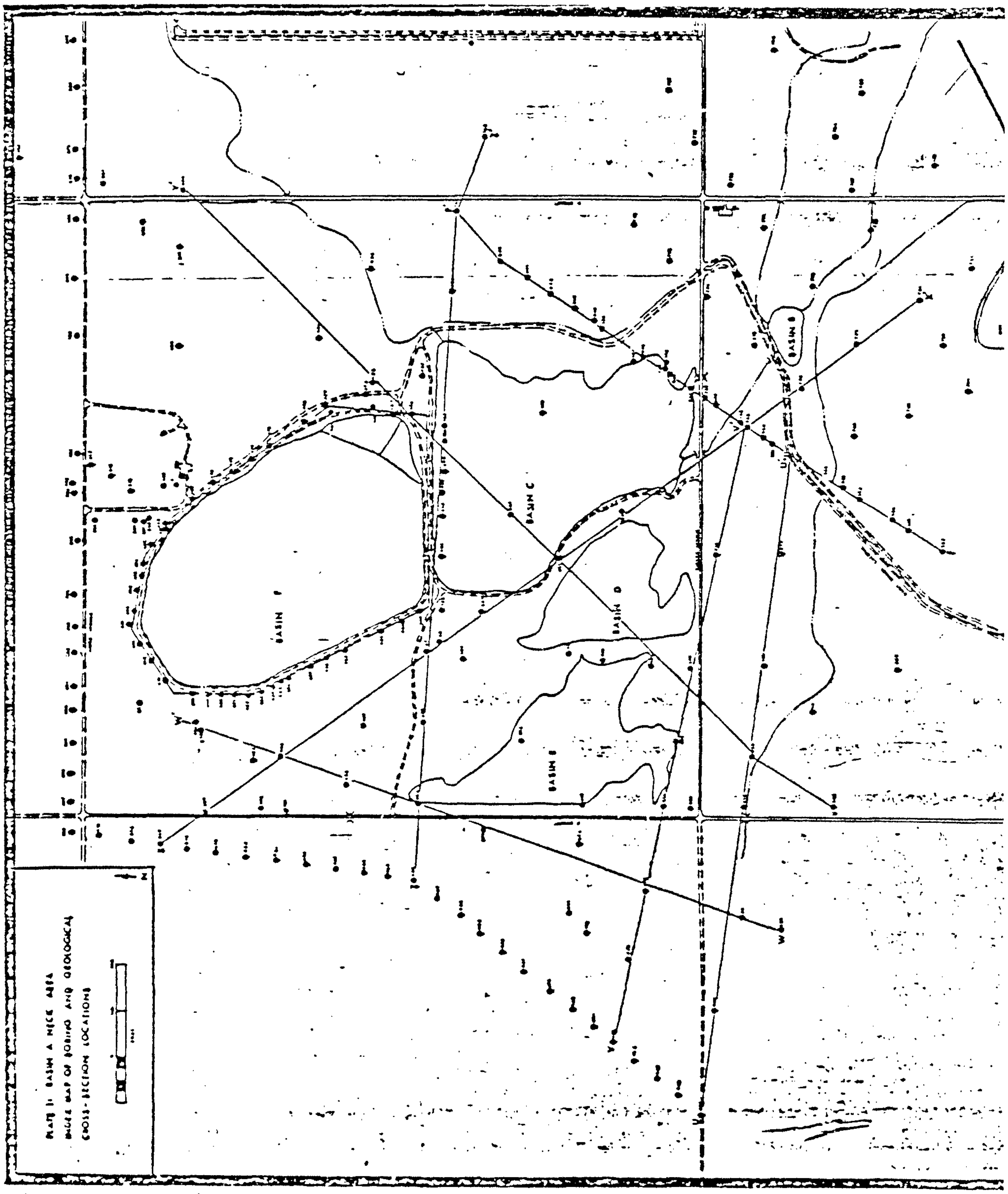


PLATE 1: BASIN A NECK AREA
INDEX MAP OF BORING AND GEOLOGICAL
CROSS-SECTION LOCATIONS
BASIN F
BASIN C
BASIN D
BASIN E
BASIN B

Plate

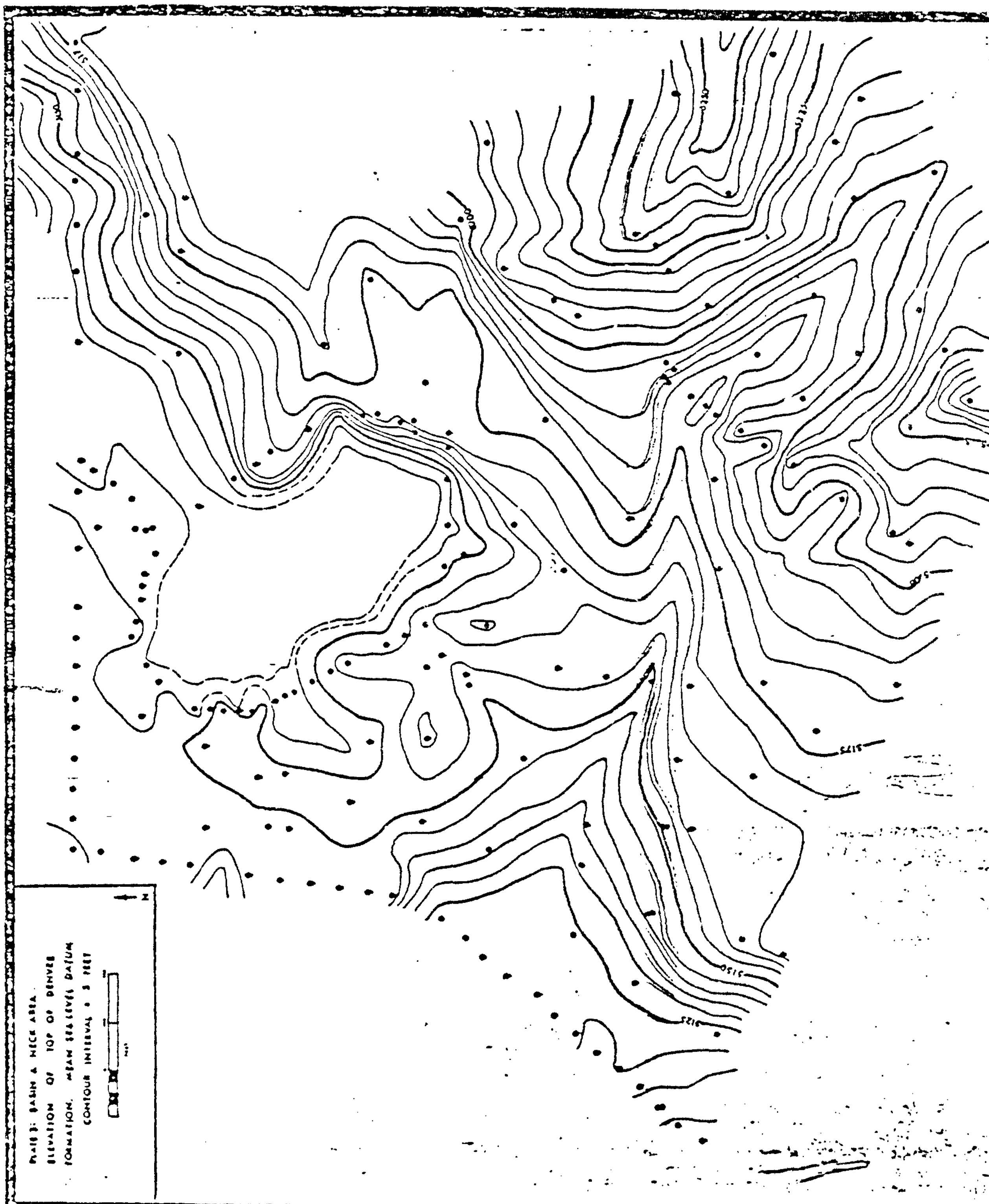
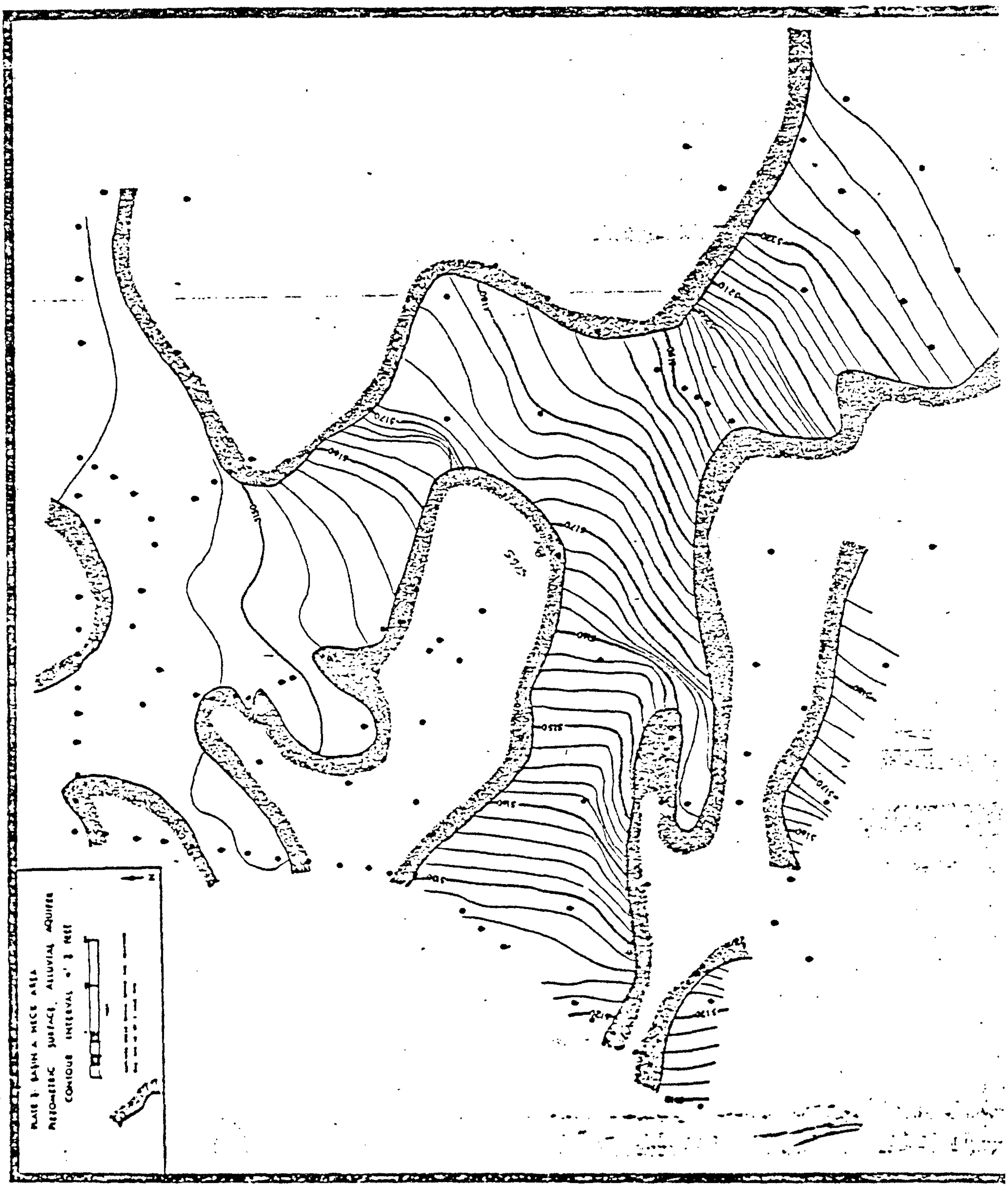

BASIN A NECK AREA.
ELEVATION OF TOP OF DENVER
FORMATION, MEAN SEA LEVEL DATUM
CONTOUR INTERVAL = 5 FEET
5125
5150
5175
5200

Plate 2



Plate

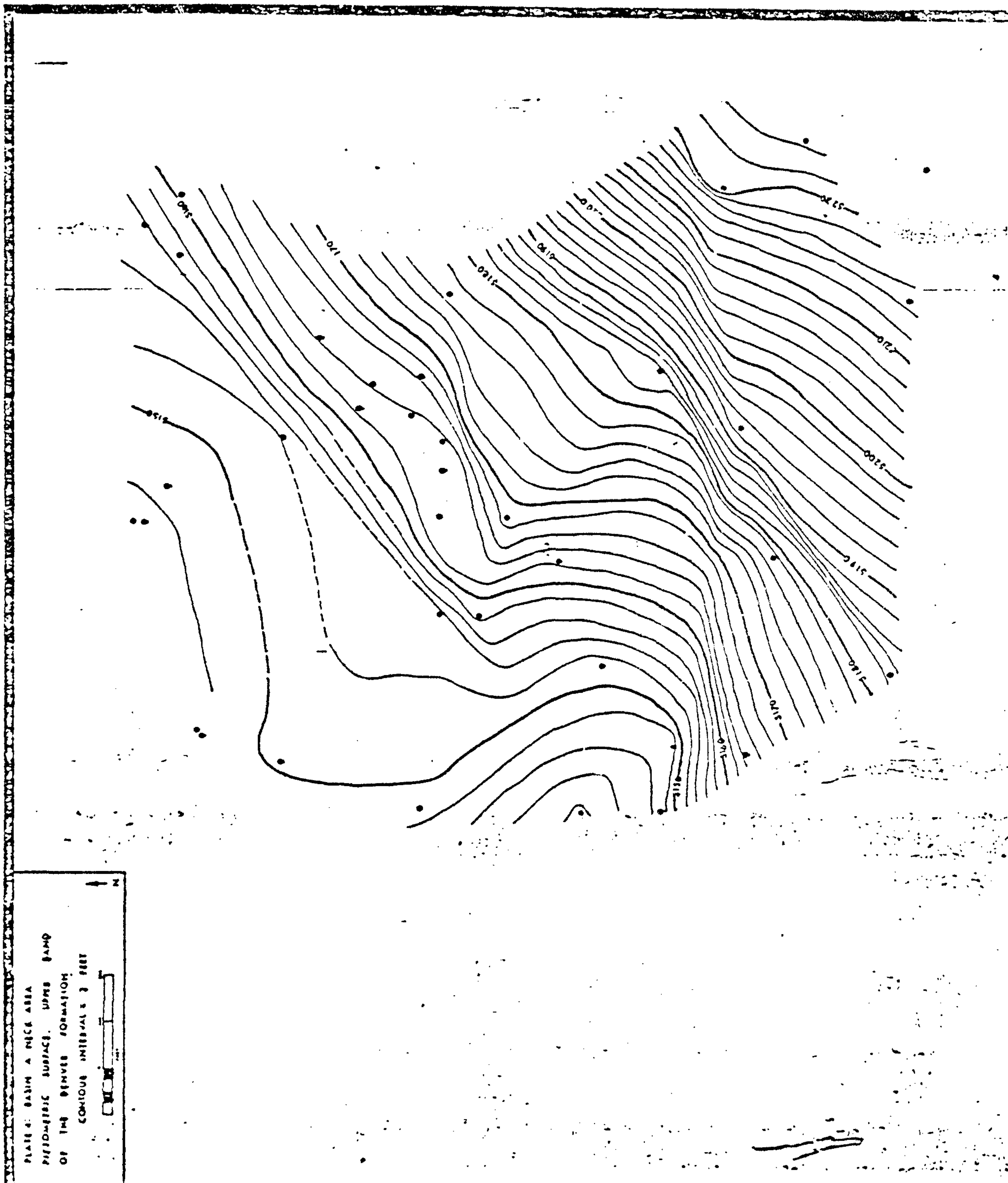
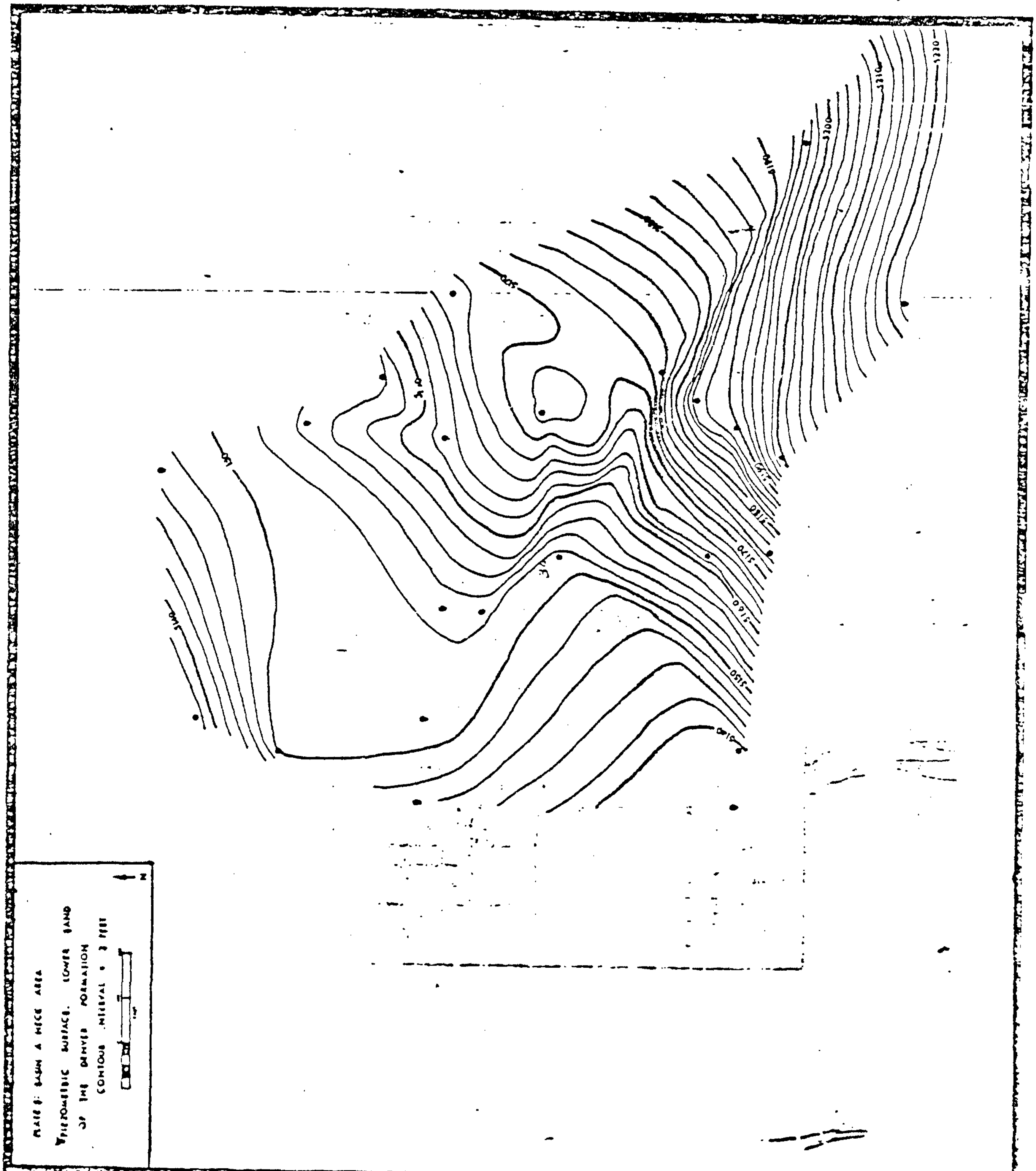


PLATE 4: BASIN A NECK AREA
PIEZOMETRIC SURFACE, UPPER SAND
OF THE DENVER FORMATION
CONTOUR INTERVALS 2 FEET
N

Plate 4


PIEZOMETRIC SURFACE. LOWER SAND
OF THE DENVER FORMATION
N

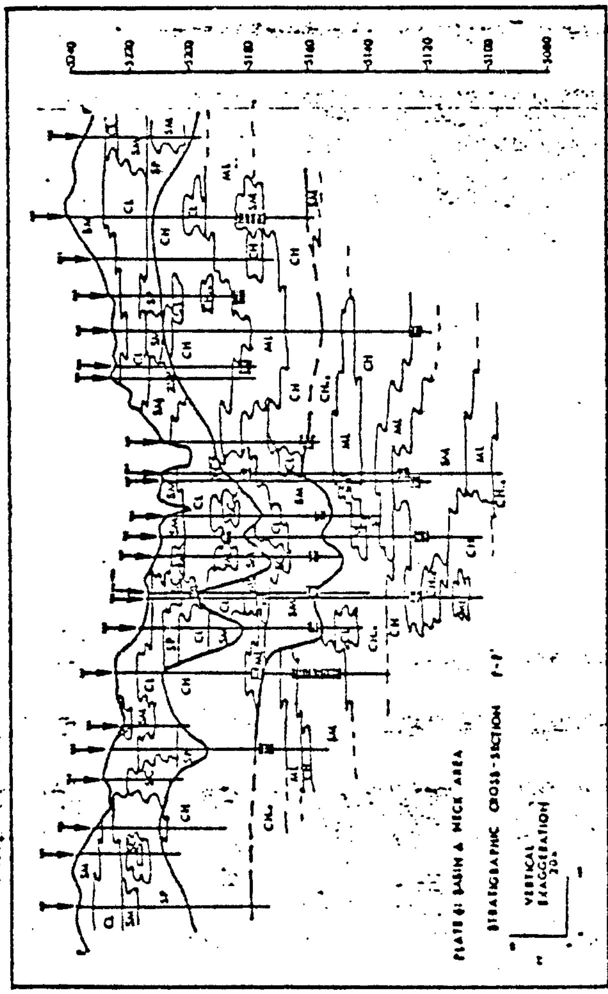


PLATE 6: BASIN & NECK AREA
STRATIGRAPHIC CROSS-SECTION
VERTICAL
EXAGGERATION

Plate 6

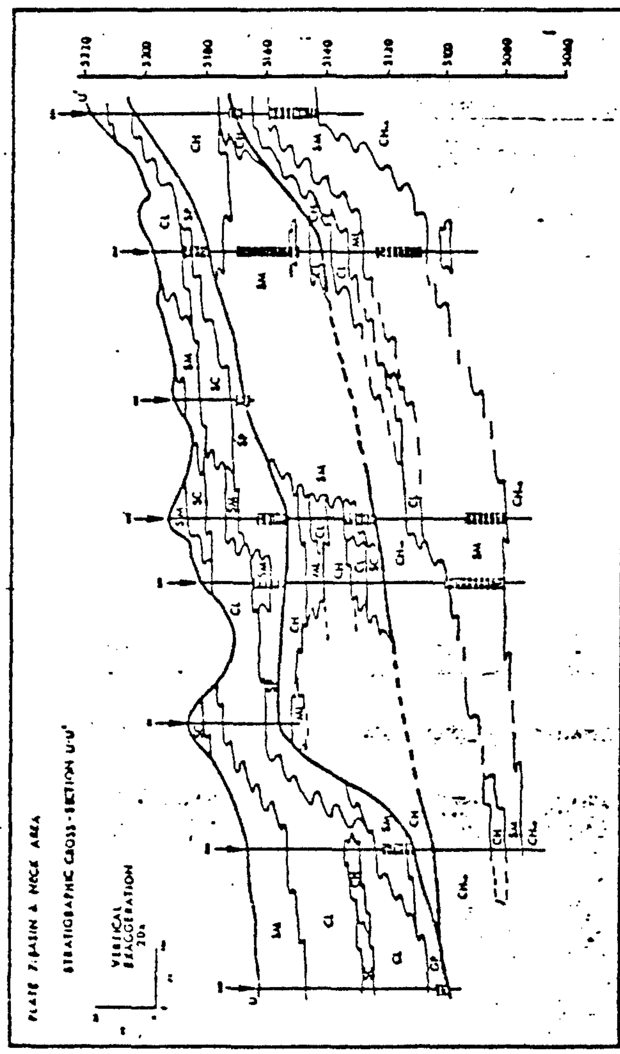


PLATE 7: BASIN & NECK AREA
STRATIGRAPHIC CROSS-SECTION U-U'
VERTICAL EXAGGERATION 20x

Plate 7

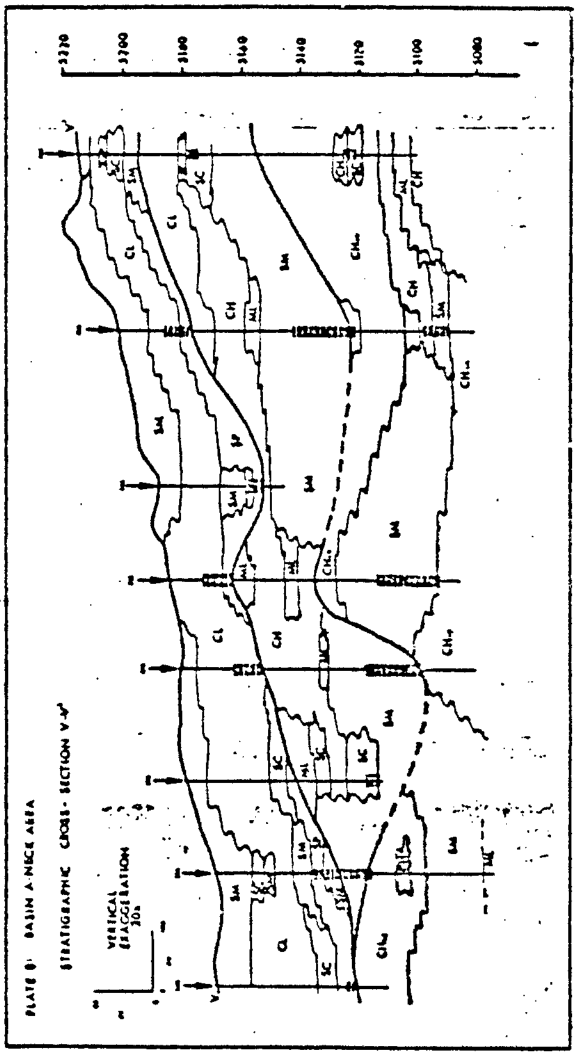


Plate 8

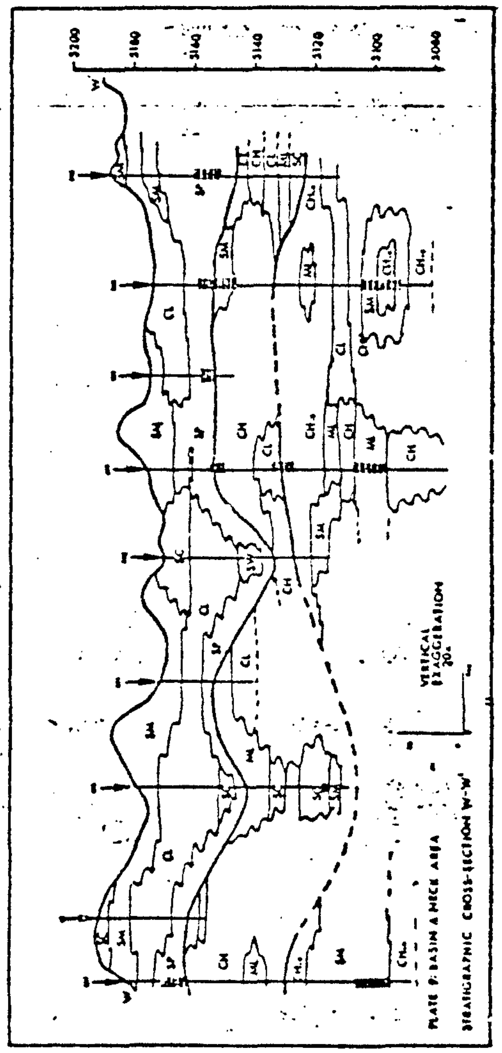
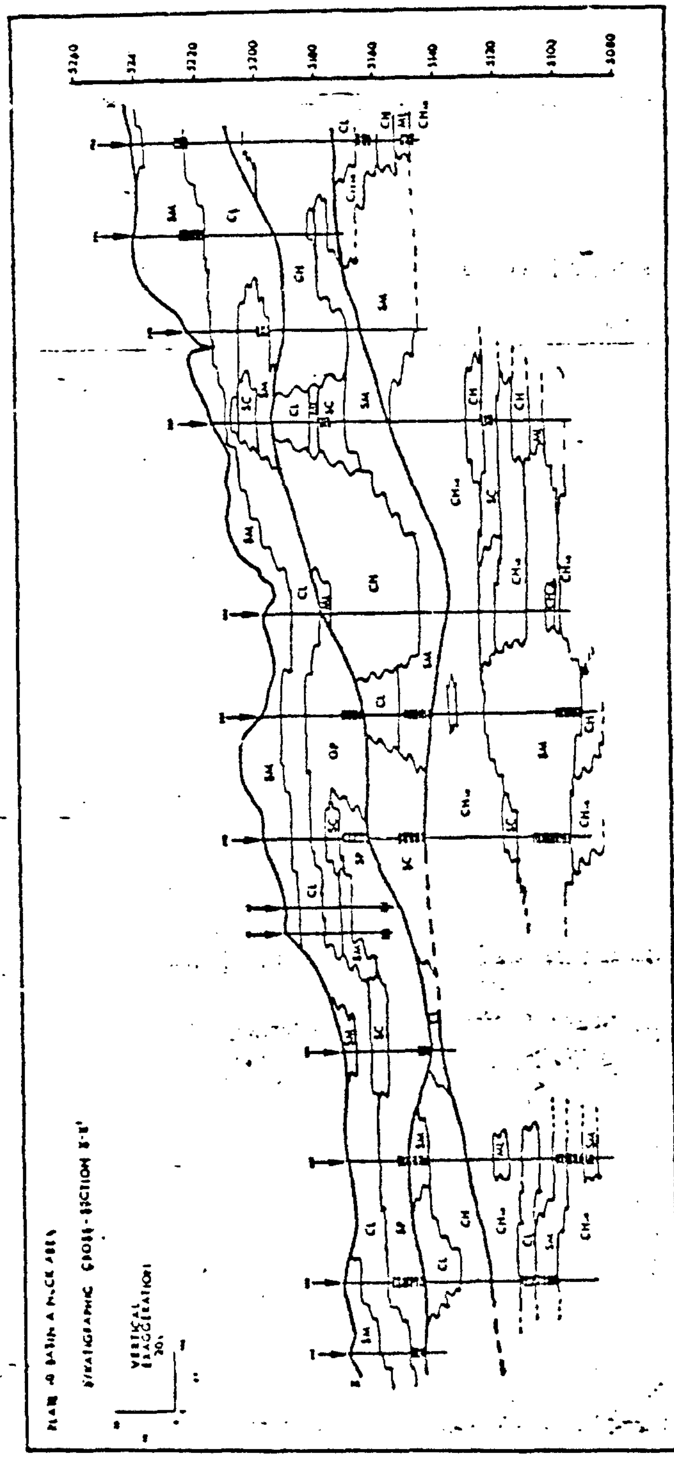


PLATE 9: BASIN A NECK AREA
STRATIGRAPHIC CROSS-SECTION W-W'
VERTICAL EXAGGERATION 20x
3200
3180
3160
3140
3120
3100
3080

Plate 9



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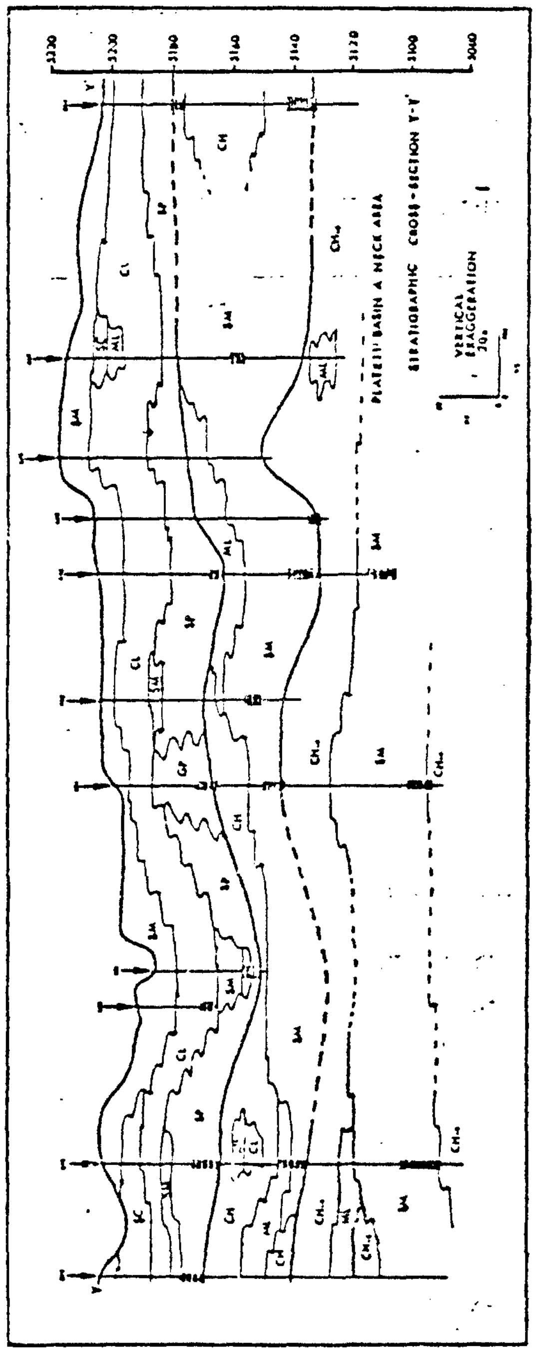

PLATEAU BASIN & NECK AREA
STRATIGRAPHIC CROSS-SECTION V-V'
VERTICAL EXAGGERATION 20x

Plate 11

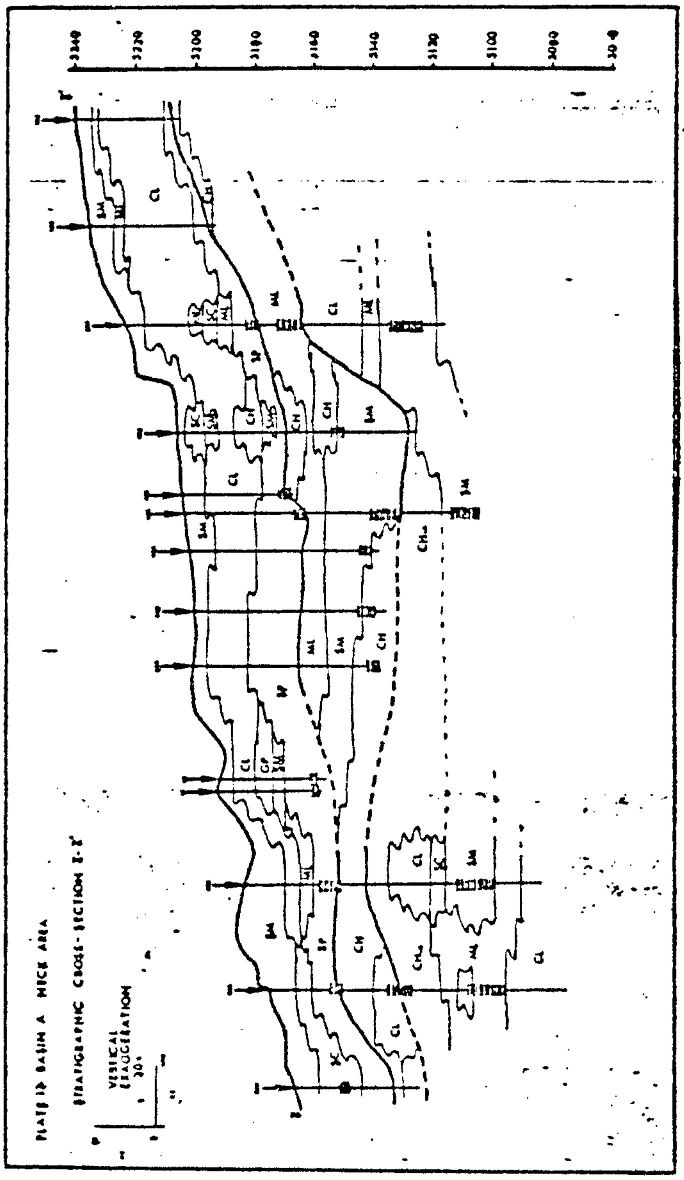


Plate 12

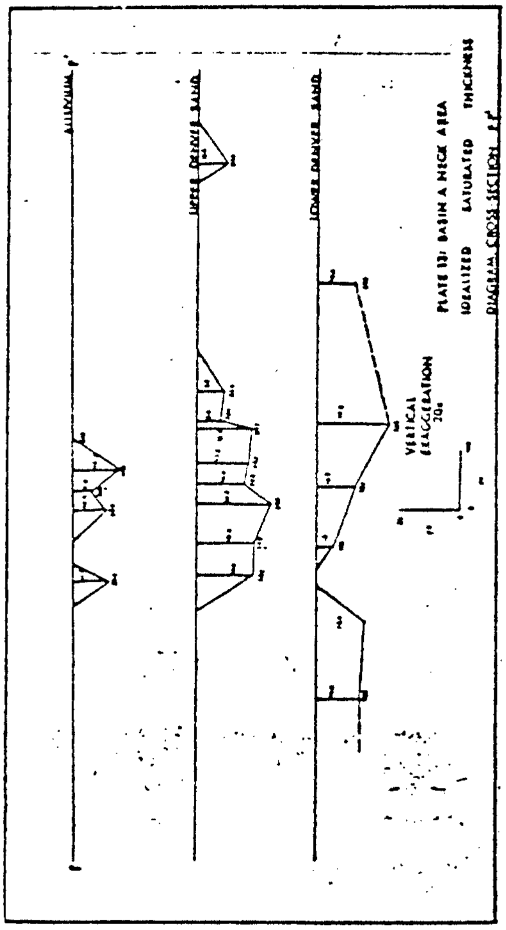


PLATE 13: BASIN A NECK AREA
IDEALIZED SATURATED THICKNESS
DIAGRAM CROSS SECTION F F'

Plate 13

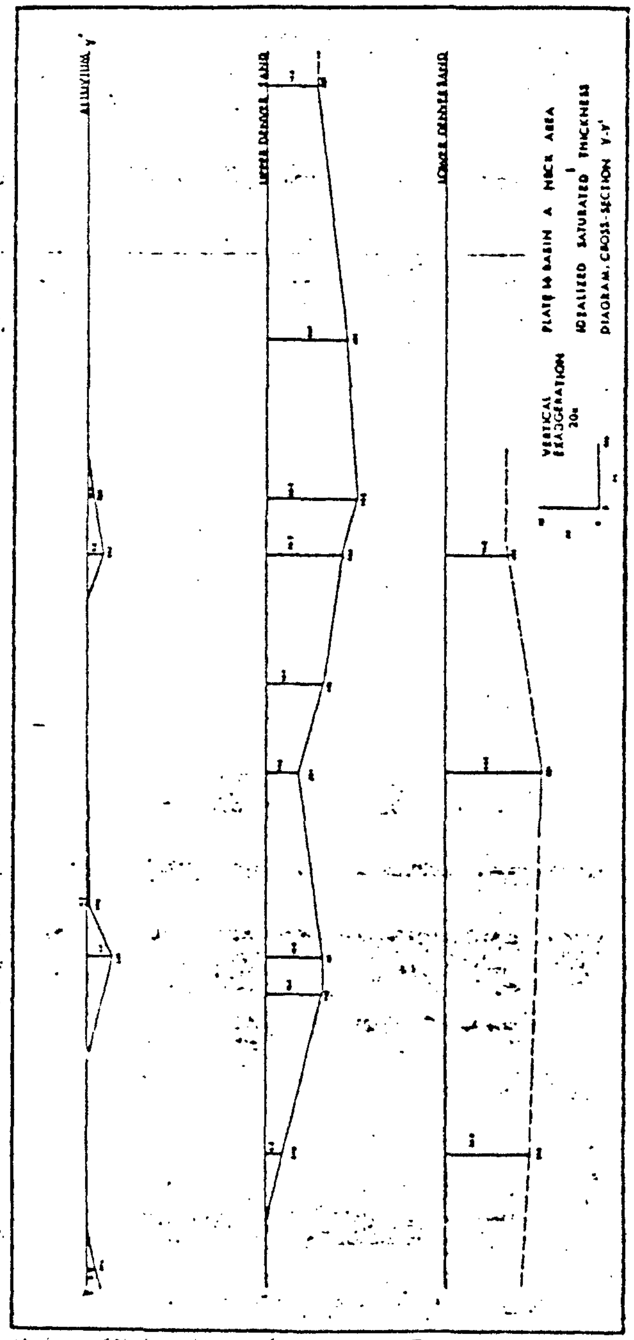


PLATE 14 BASIN A NECK AREA
IDEALIZED SATURATED THICKNESS
DIAGRAM, CROSS-SECTION Y-Y'
VERTICAL EXAGGERATION 20x
ALLUVIUM
UPPER DENVER SAND
LOWER DENVER SAND

Plate 14

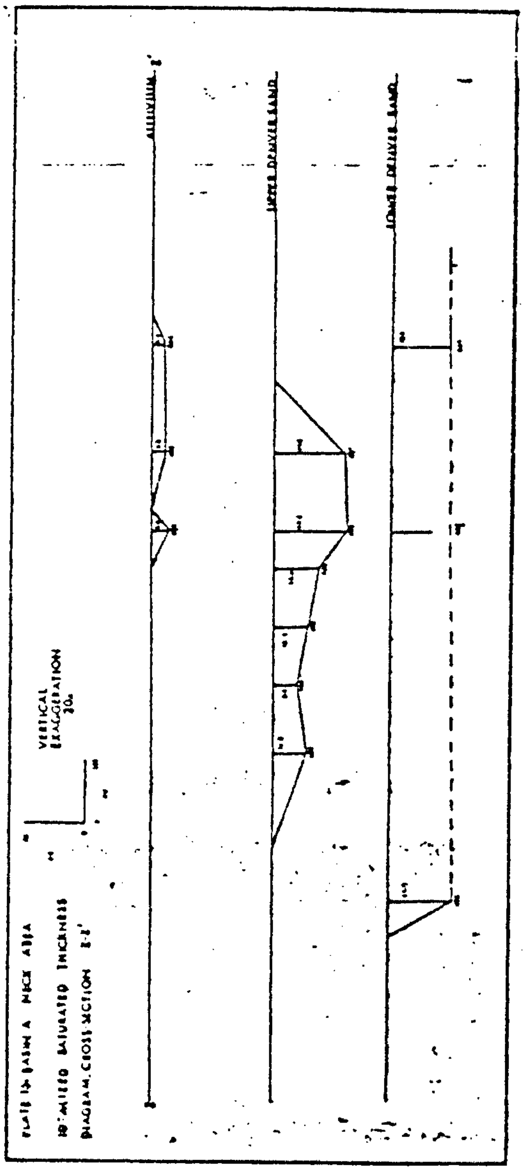

VERTICAL EXAGGERATION
ALLUVIUM
UPPER DENVER SAND
LOWER DENVER SAND

Plate 15

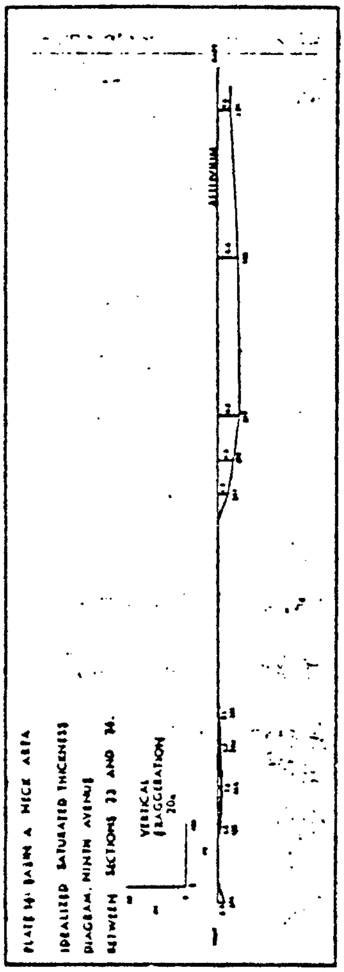

BASIN A NECK AREA
IDEALIZED SATURATED THICKNESS
DIAGRAM, NINTH AVENUE
VERTICAL
EXAGGERATION
ALLUVIUM

Plate 16

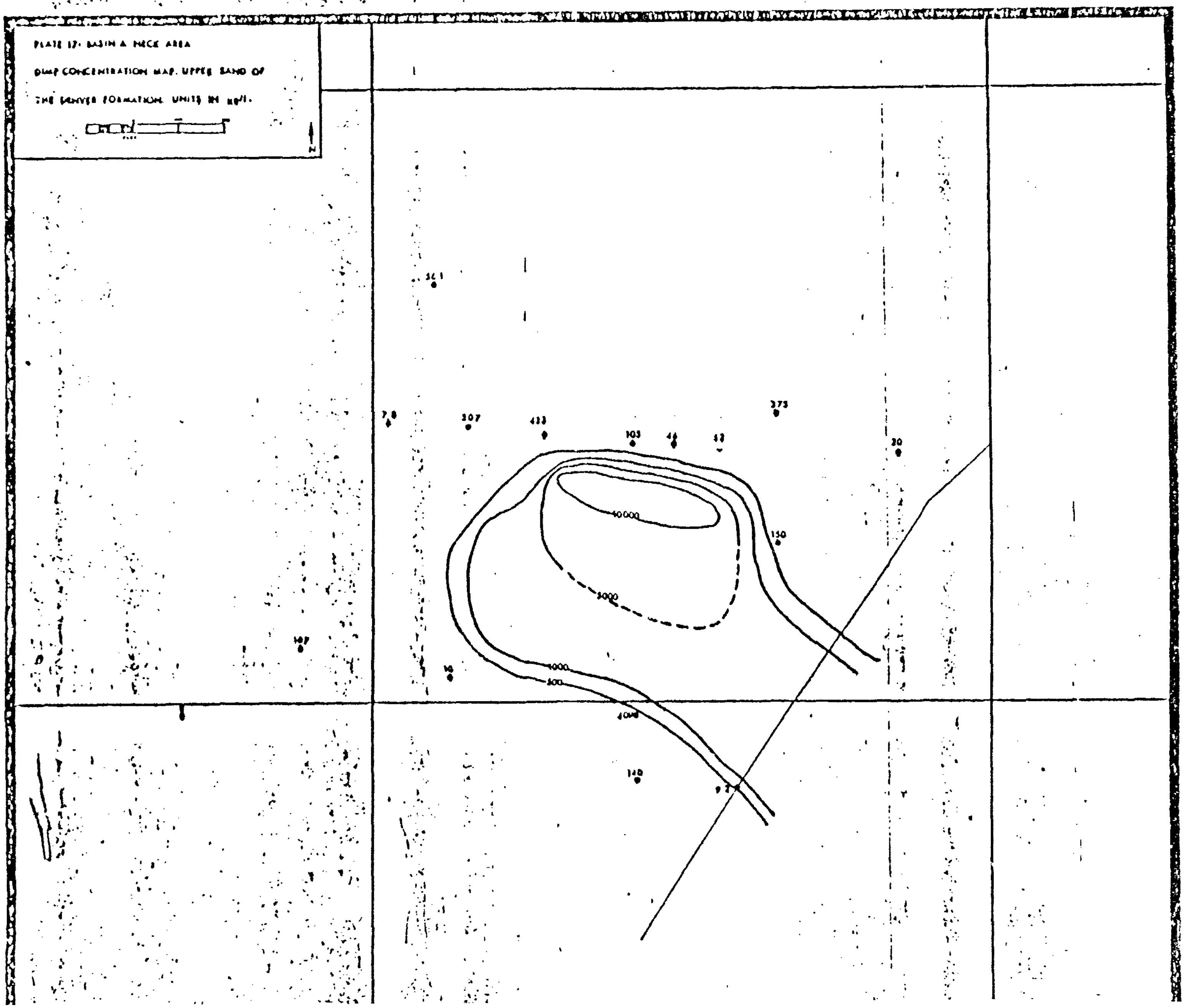


PLATE 17: BASIN A NECK AREA
DIMP CONCENTRATION MAP, UPPER SAND OF
THE DENVER FORMATION. UNITS IN µg/l.
N
10000
5000
1000
500

Plate

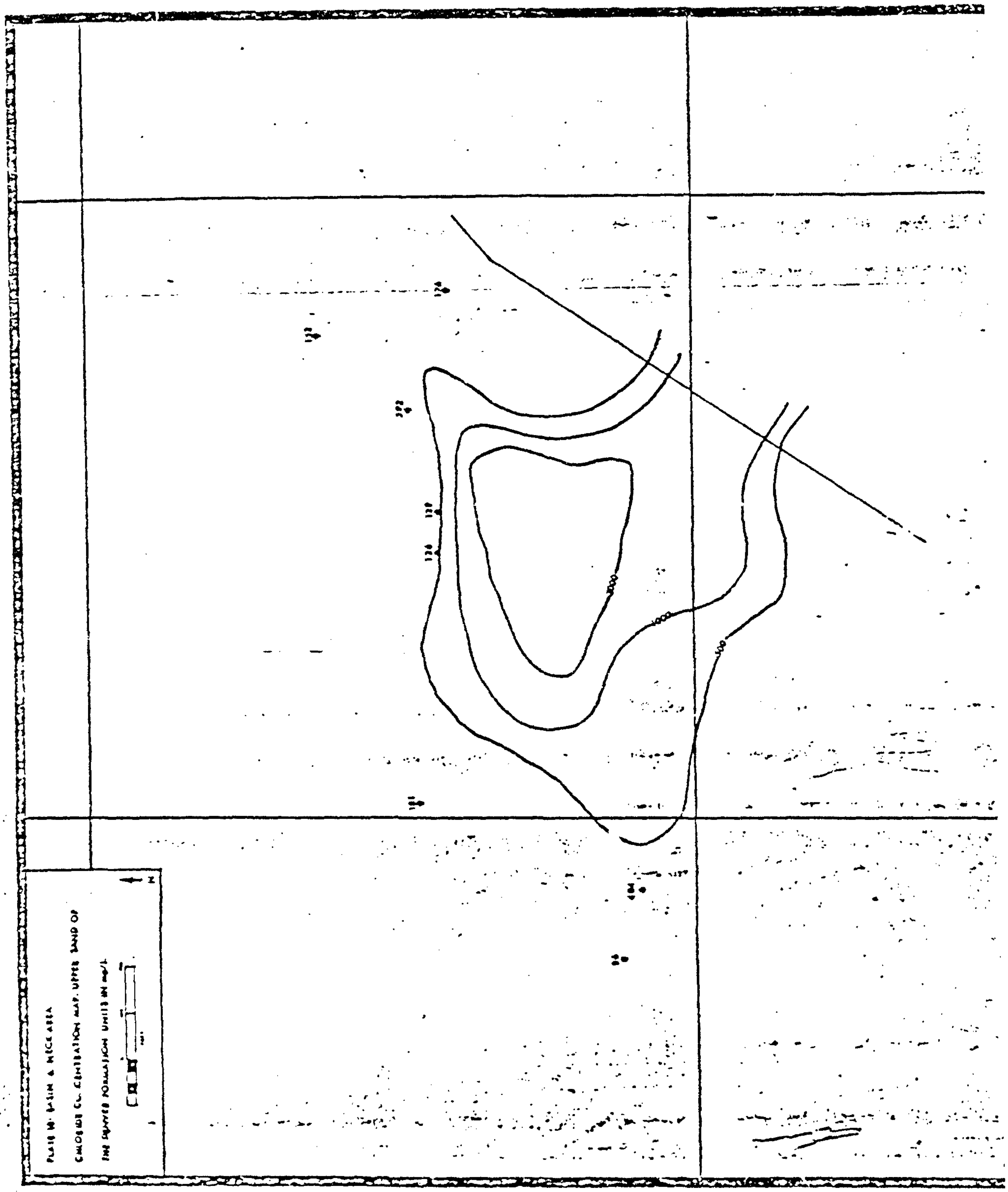
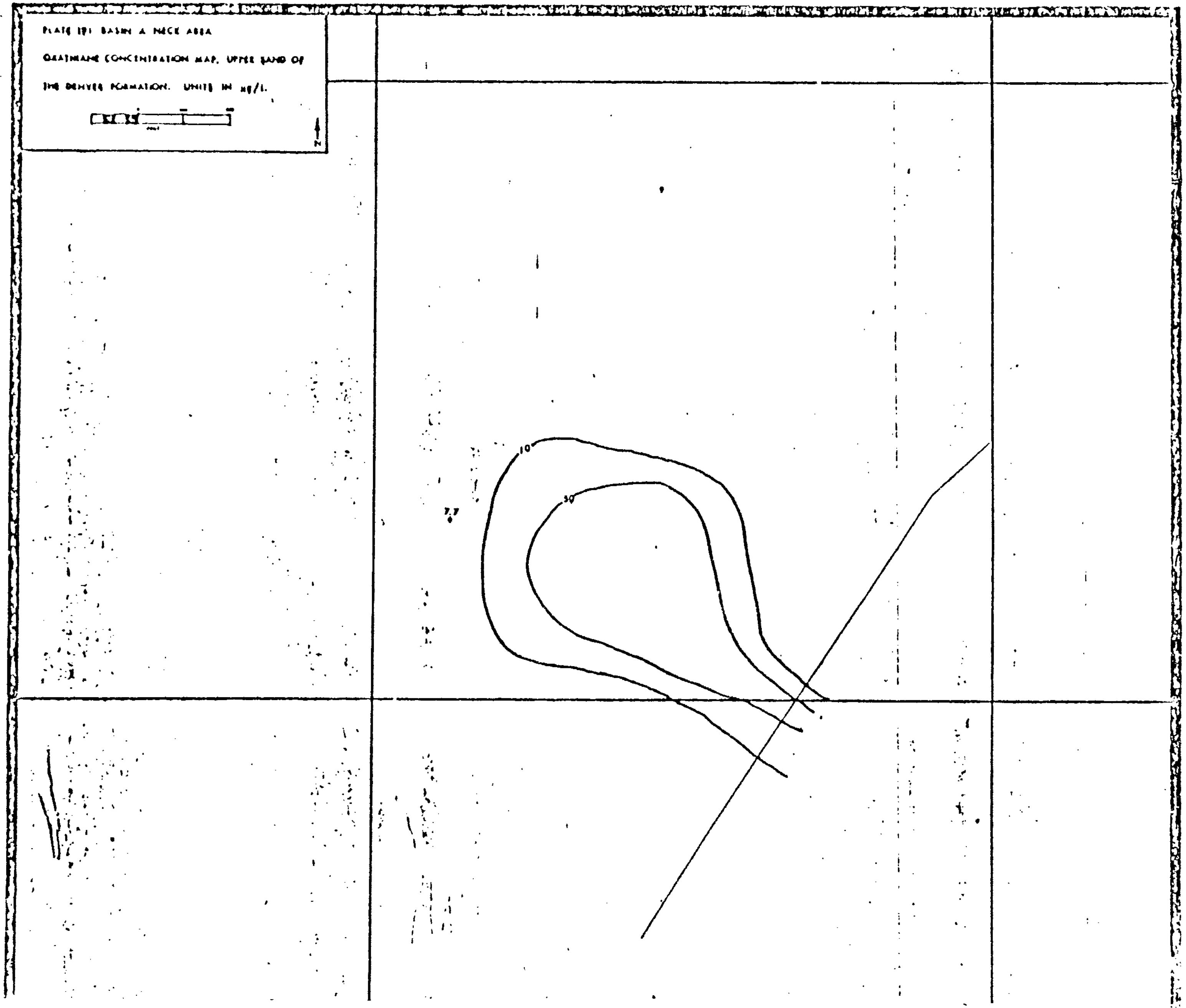


Plate 18


BASIN A NECK AREA
OXATHIANE CONCENTRATION MAP, UPPER SAND OF
THE DENVER FORMATION. UNITS IN µg/l.
N
10
50

Plate

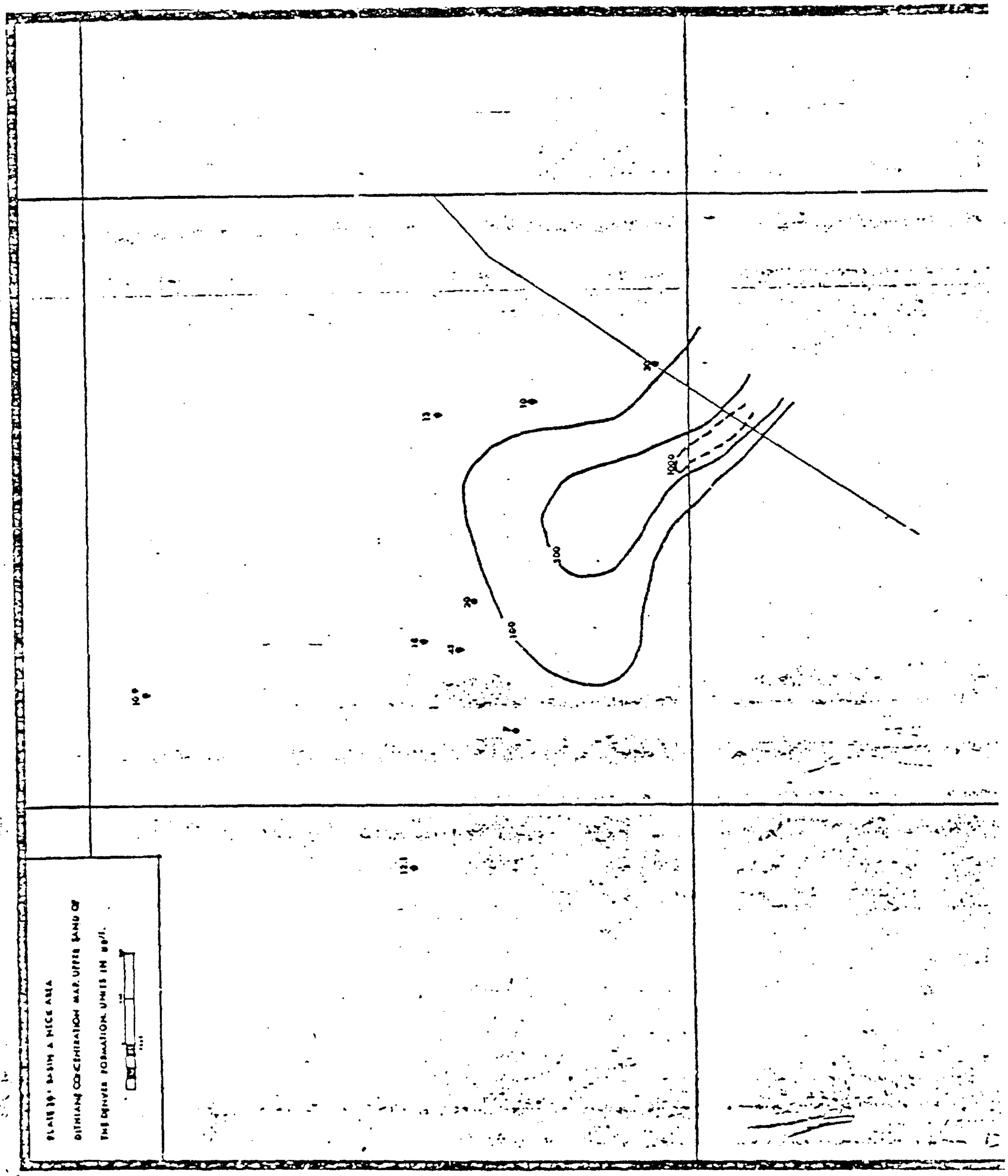


PLATE 20: BASIN A NECK AREA
DITHIANE CONCENTRATION MAP, UPPER SAND OF
THE DENVER FORMATION. UNITS IN ug/l.
100
100
100

Plate 20

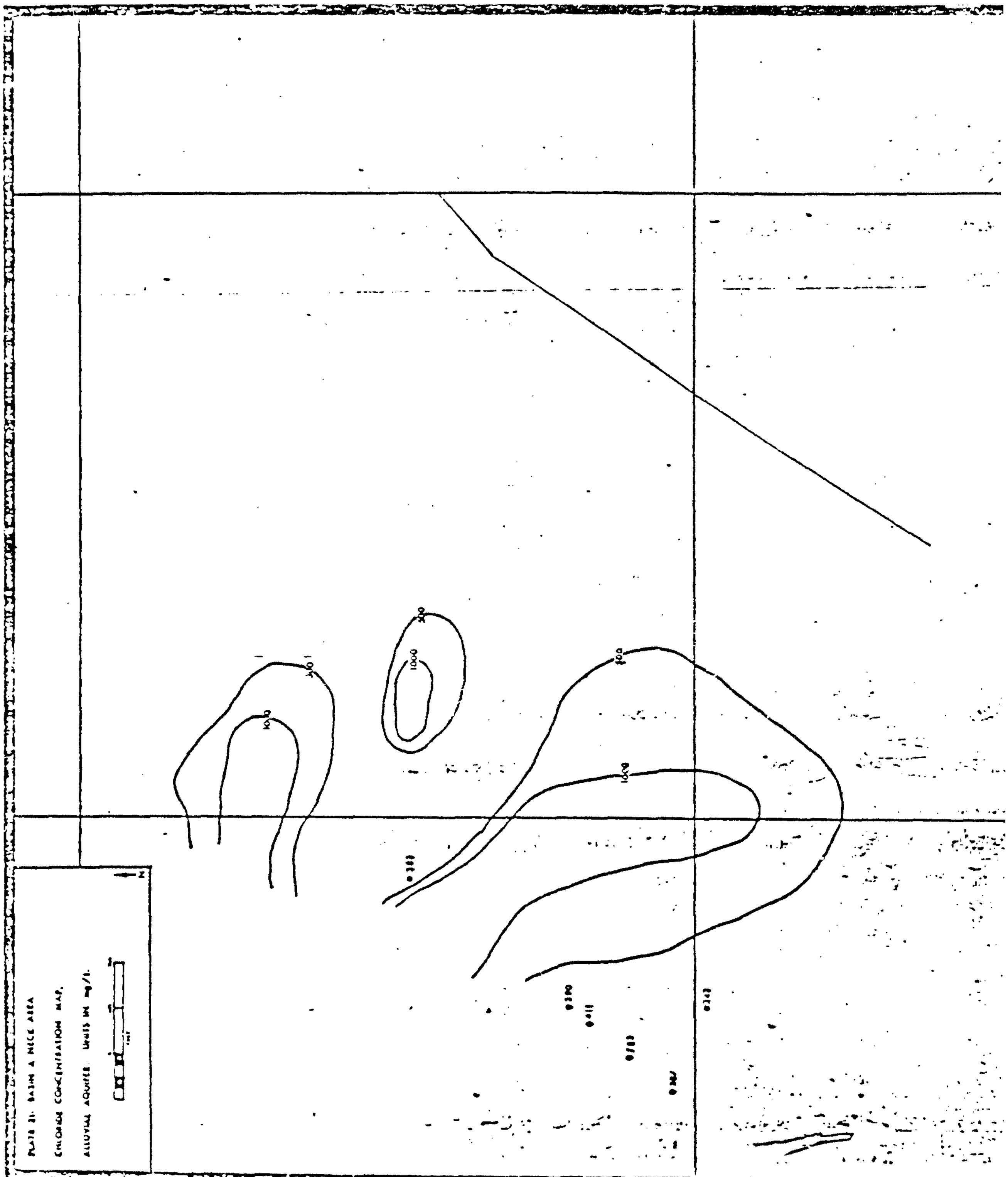


PLATE 21. BASIN A NECK AREA
CHLORIDE CONCENTRATION MAP.
ALLUVIAL AQUIFER. UNITS IN mg/l.
N

Plate 2

Table 1: Summary of Boring Data, Basin A Neck Area, Rocky Mountain Arsenal.

WORKING DRAFT

Boring No.	Drilling Date	Driller and Rig Type	Total Depth (ft)	Depth to Top of Denver Formation (ft)	Elevation of Ground (ft, MSL)	Elevation Top of Denver Formation (ft)	USCS, Top of Denver Formation	Screen Interval (ft)	Aquifer Screened	Elevation Top of Casing (ft, MSL)	Undisturbed Sample Interval (ft)	Mid-Screen Elevation (ft, MSL)	USCS of Screened Interval
601	10 Oct 78	Contract-A	107.4	34.5	5198.7	5164.2	CL	--	--	--	--	--	--
601	9 Nov 78	Taylor-A	39.5	--	--	--	--	27.4-34.5	ALL	5200.5	--	5167.8	GP
601	17 Oct 78	Stewart-R	62.0	--	--	--	--	49.0-57.0	UDS	5200.5	55.0-57.5	5145.7	SM
601	[illegible] Oct 78	Stewart-R	112.0					99.0-107.0	LDS	5200.9	105.0-107.4	5095.7	SM
602	12 Oct 78	Contract-A	109.3	30.1	5188.4	5158.3	CL	--	--	--	--	--	--
602	16 Nov 78	Taylor-A	35.1	--	--	--	--	20.1-30.1	ALL	5191.1		5163.3	SM
502	20 Oct 78	Stewart-R	84.5	--	--	--	--	67.5-79.5	UDS	5190.3	75.0-76.5 77.5-80.0	5114.9	SM
603	13 Oct 78	Contract-A	104.5	34.0	5199.0	5165.0	ML	--	--	--	--	--	--
603	10 Nov 78	Taylor-A	39.0	--	--	--	--	26.0-34.0	ALL	5201.1	--	5169.0	SP
603	23 Oct 78	Stewart-R	59.0	--	--	--	--	46.0-54.0	UDS	5200.8	50.0-52.5	5149.0	SM
603	24 Oct 78	Stewart-R	109.0	--	--	--	--	92.0-104.0	LDS	5201.1	100.0-101.8	5101.0	CH
604	18 Oct 78	Contract-A	109.8	50.2	5223.0	5172.8	ML	--	--	--	--	--	--
604	15 Nov 78	Taylor-A	55.2	--	--	--	--	46.2-50.2	ALL	5225.7	--	5174.8	SP
604	25 Oct 78	Stewart-R	64.0	--	--	--	--	51.0-59.0	UDS	5224.8	54.0-56.5	5168.0	ML
604	23 Oct 78	Stewart-R	104.5	--	--	--	--	88.5-99.5	LDS	5225.0	*	5129.0	CH
605	19 Oct 78	Contract-A	99.5	32.5	5183.8	5161.3	CH	--	--	--	--	--	--
605	10 Nov 78	Taylor-A	37.5	--	--	--	--	25.4-32.5	ALL	5185.8		5154.9	SP
605	30 Oct 78	Stewart-R	89.5	--	--	--	--	72.5-84.5	LDS	5186.4	76.0-78.5	5105.3	CH
606	21 Oct 78	Contract-A	100.0	25.5	5175.1	5149.6	CH	--	--	--	--	--	--
606	13 Nov 78	Taylor-A	30.5	--	--	--	--	21.2-25.5	ALL	5178.0	--	5151.8	SP
606	2 Nov 78	Stewart-R	54.0	--	--	--	--	41.0-49.0	UDS	5177.8	*	5130.1	CL
606	31 Oct 78	Stewart-R	85.0	--	--	--	--	68.0-80.0	LDS	5177.9	74.0-76.5	5101.1	ML
607	26 Oct 78	Contract-A	85.3	27.6	5173.8	5146.2	CL	--	--	--	--	--	--
607	11 Nov 78	Taylor-A	32.6	--	--	--	--	17.9-27.6	ALL	5176.3	--	5151.1	SP
607	8 Nov 78	Stewart-R	77.0	--	--	--	--	60.0-72.0	LDS	5175.8	69.0-71.5	5107.8	SM
608	24 Oct 78	Contract-A	89.7	20.5	5172.8	5152.3	SM	--	--	--	--	--	--
608	6 Nov 78	Taylor-A	32.0	--	--	--	--	17.0-27.0	ALL/UDS	5175.1	--	5150.8	SP/SM
608	7 Nov 78	Stewart-R	87.0	--	--	--	--	70.0-82.0	LDS	5174.7	79.0-81.2	5096.8	SM
609	17 Nov 78	Taylor-A	99.2	32.1	5210.5	5178.4	ML	--	--	--	--	--	--
609	20 Nov 78	Taylor-A	37.1	--	--	--	--	22.9-32.1	ALL	5212.4	--	5183.0	SP
609	21 Nov 78	Stewart-R	89.0	--	--	--	--	64.0-84.0	UDS/LDS	5212.3	55.0-57.5 75.0-77.5	5136.5	SM/SM
610	27 Oct 78	Contract-A	74.8	35.0	5187.3	5152.3	ML	--	--	--	--	--	--
610	11 Nov 78	Taylor-A	40.0	--	--	--	--	27.7-35.0	ALL/UDS	5189.55	--	5156.0	GP/ML
611	1 Nov 78	Contract-A	84.5	43.5	5167.9	5124.4	CH	--	--	--	--	--	--
611	13 Nov 78	Taylor-A	40.2	--	--	--	--	25.2-35.2	ALL	5170.5	--	5137.7	SP
612	30 Oct 78	Contract-A	89.6	36.0	5172.0	5136.0	CH	--	--	--	--	--	--
612	13 Nov 78	Taylor-A	41.0	--	--	--	--	32.0-36.0	ALL	5174.7	--	5138.0	SP
612	3 Nov 78	Stewart-R	74.0	--	--	--	--	57.0-69.0	UDS	5173.0	55.0-57.5	5109.0	SM
612	4 Nov 78	Stewart-R	89.0	--	--	--	--	76.0-84.0	LDS	5173.3	79.0-81.5	5092.0	SM
613	16 Nov 78	Contract-A	95.0	42.0	5168.3	5126.3	SM	--	--	--	--	--	--
613	18 Nov 78	Taylor-A	58.8	--	--	--	--	33.8-53.8	ALL/UDS	5169.9	--	5124.5	SP/SM
614	14 Nov 78	Contract-A	99.9	26.7	5179.4	5152.7	CH	--	--	--	--	--	--
614	17 Nov 78	Taylor-A	31.9	--	--	--	--	17.7-26.9	ALL	5182.2	--	5157.1	CL
614	20 Nov 78	Stewart-R	88.0	--	--	--	--	63.0-83.0	UDS	5181.3	50.0-52.5 70.0-70.9	5106.4	SM
615	13 Nov 78	Contract-A	99.0	20.7	5183.0	5162.3	ML	--	--	--	--	--	--
615	17 Nov 78	Taylor-A	25.7	--	--	--	--	10.7-20.7	ALL	5184.6	--	5167.3	SP

(Continued)

* Undisturbed sample attempted three times--no sample recovered.

WORKING DRAFT

Table 11. (Continued)

Boring No.	Drilling Date	Driller and Rig Type	Total Depth (ft)	Depth to Top of Denver Formation (ft)	Elevation of Ground (ft, MSL)	Elevation Top of Denver Formation (ft)	USCS, Top of Denver Formation	Screen Interval (ft)	Aquifer Screened	Elevation Top of Casing (ft, MSL)	Undisturbed Sample Interval (ft)	Mid-Screen Elevation (ft, MSL)	USCS of Screened Interval
815	17 Nov 78	Stewart-R	96.0	--	--	--	--	71.0-91.0	UDS	5184.8	75.0-77.5	5102.0	SM
816	6 Nov 78	Contract-A	119.6	25.0	5200.1	5175.1	CL	--	--	--	--	--	--
815	17 Nov 78	Taylor-A	30.0	--	--	--	--	15.0-25.0	ALL	5201.9	--	5180.1	SP
816	16 Nov 78	Stewart-R	64.0	--	--	--	--	59.0-79.0	UDS	5202.2	60.0-62.3	5131.1	SM
816	14 Nov 78	Stewart-R	117.0	--	--	--	--	104.0-112.0	LDS	5201.5	109.0-110.6	5092.0	SM
817	9 Nov 78	Contract-A	104.3	17.0	5207.0	5190.0	CH	--	--	--	--	--	--
817	14 Nov 78	Taylor-A	23.2	--	--	--	--	10.0-18.2	ALL	5210.3	--	5192.9	SP
817	24 Nov 78	Stewart-R	53.0	--	--	--	--	28.0-48.0	UDS	5207.9	35.0-36.3	5169.0	SM
817	22 Nov 78	Stewart-R	54.0	--	--	--	--	74.0-89.0	LDS	5208.3	80.0-81.9	5125.5	SM
818	2 Nov 78	Contract-A	119.6	36.0	5202.5	5166.5	CH	--	--	--	--	--	--
818	14 Nov 78	Taylor-A	44.1	--	--	--	--	30.0-39.1	ALL	5204.2	--	5168.0	SP
818	10 Nov 78	Stewart-R	72.0	--	--	--	--	59.0-67.0	UDS	5204.4	62.0-64.5	5139.5	SM
818	13 Nov 78	Stewart-R	117.0	--	--	--	--	100.0-112.0	LDS	5204.2	100.0-102.5 110.0-112.4	5096.5	SM
819	22 Nov 78	Taylor-A	109.0	27.6	5191.3	5163.7	CH	--	--	--	--	--	--
819	23 Nov 78	Taylor-A	33.0	--	--	--	--	18.0-28.0	ALL	5193.0	--	5166.3	SP
819	25 Nov 78	Stewart-R	107.0	--	--	--	--	82.0-102.0	LDS	5193.2	90.0-92.5	5099.3	SM
820	25 Nov 78	Taylor-A	100.5	56.0	5175.5	5119.5	CH	--	--	--	--	--	--
820	25 Nov 78	Taylor-A	61.0	--	--	--	--	46.0-56.0	ALL	5177.5	--	5124.5	SP
821	1 Dec 78	Taylor-A	95.5	20.4	5186.8	5166.4	CH	--	--	--	--	--	--
821	22 Dec 78	Heick-A	25.5	--	--	--	--	15.5-20.5	ALL	5189.1	--	5169.1	SP
822	2 Dec 78	Taylor-A	115.5	34.2	5200.2	5166.0	CH	--	--	--	--	--	--
822	12 Dec 78	Heick-A	40.0	--	--	--	--	27.0-35.0	ALL	5202.8	--	5161.8	SP
823	30 Nov 78	Heick-A	81.5	33.0	5213.9	5180.9	ML	--	--	--	--	--	--
823	8 Dec 78	Heick-A	38.0	--	--	--	--	25.0-33.0	ALL	5216.6	--	5184.9	SP
823	30 Nov 78	Stewart-R	70.0	--	--	--	--	45.0-65.0	UDS/LDS	5215.3	50.0-52.5 60.0-62.5	5158.9	SM/SM
824	6 Dec 78	Taylor-A	85.5	24.0	5208.3	--	SM	--	--	--	--	--	--
824	30 Apr 78	Heick-A	29.0	--	--	--	--	20.0-24.0	ALL/UDS	5210.2	--	5186.3	SP/SM
824	10 Apr 79	Warhurst-R	76.2	--	--	--	--	61.2-71.2	UDS	5210.6	*	5142.1	SM
825	16 Apr 79	Warhurst-R	104.5	46.5	5220.9	5174.5	CH	78.0-98.0	UDS/LDS	5223.2	*	5132.9	SM/SM
825	1 May 79	Heick-A	51.5	--	--	--	--	42.5-46.5	ALL	5223.2	--	5176.4	SP
826	20 Apr 79	Heick-A	96.5	24.8	5257.3	5222.5	CL	--	--	--	--	--	--
827	18 Apr 79	Heick-A	101.5	38.0	5197.1	5159.1	CH	--	--	--	--	--	--
827	18 Apr 79	Warhurst-R	80.0	--	--	--	--	65.0-75.0	LDS	5199.9	*	5127.1	SM
651**	3 Nov 78	Taylor-A	90.5	15.5	5225.9	5210.4	CH	--	--	--	--	--	--
651**	4 Nov 78	Taylor-A	55.0	--	--	--	--	46.6-50.0	UDS	5228.4	--	5177.6	ML
651**	15 Nov 78	Stewart-R	81.0	--	--	--	--	59.0-76.0	LDS	5228.4	70.0-72.5	5158.4	SM
640**	28 Nov 78	Stewart-R	72.0	--	5240.6	--	CH	57.0-67.0	UDS	5242.3	*	5178.6	SM
655**	6 Dec 78	Stewart-R	78.0	--	5203.8	--	ML	63.0-73.0	UDS	5206.9	*	5135.8	SM
655**	5 Dec 78	Stewart-R	105.0	--	--	--	--	90.0-100.0	LDS	5205.7	95.0-97.5	5108.8	SM

* No undisturbed samples taken.
** Redrill of previously drilled boring.

Table 2: Summary of Permeability Data, Basin A Neck Area, Rocky Mountain Arsenal.

Boring No.	Type of Test*	Analytical Method**	Aquifer Screened***	K (cm/sec) (x 10^{-4})	K (ft/day)	K (gal/day/ft^2)
723	SLUG	C	UDS	9.850	2.79	20.88
723	SLUG	C	LDS	0.137	0.04	0.29
724	FHT	C	UDS	4.150	1.18	8.80
724	SLUG	C	LDS	19.500	5.53	41.13
725	FHT	C	ALL	1.600	0.45	3.39
725	SLUG	C	LDS	5.460	1.55	11.58
455	SLUG	C	UDS	12.150	3.44	25.76
455	SLUG	C	LDS	18.320	5.19	38.84
493	SLUG	C	UDS	22.430	6.36	47.56
493	SLUG	C	LDS	0.013	0.01	0.03
496†	SLUG	C	UDS	71.200	20.18	150.96
496	SLUG	C	LDS	19.360	5.49	41.05
801	SLUG	C	UDS	3.497	0.99	7.41
801	SLUG	C	LDS	7.238	2.05	15.35
802	SLUG	C	UDS	7.281	2.06	15.44
803	FHT	B&R	ALL	1.134	0.32	2.40
803	SLUG	C	UDS	11.530	3.27	24.45
803	SLUG	C	LDS	19.030	5.39	40.35
804	FHT	B&R	ALL	41.990	11.90	89.03
804	SLUG	C	LDS	7.232	2.05	15.33
806	SLUG	C	LDS	0.202	0.06	0.43
807	FHT	B&R	ALL	2.277	0.65	4.83
808	FHT	C	ALL	2.441	0.69	5.18
809	FHT	C	ALL	9.735	2.76	20.64
809	SLUG	C	LDS	6.766	1.92	14.35
810	FHT	C	ALL	5.986	1.70	12.69
812	FHT	B&R	ALL	0.438	0.12	0.93
812	SLUG	C	UDS	22.800	6.46	48.34
812	SLUG	C	LDS	21.320	6.04	45.20
814	SLUG	C	UDS	5.509	1.56	11.68
815	FHT	B&R	ALL	0.083	0.02	0.18
815	SLUG	C	UDS	3.866	1.10	8.20
816	SLUG	C	UDS	7.733	2.19	16.40
817	SLUG	C	LDS	3.495	0.99	7.41
818	SLUG	C	UDS	2.450	0.69	5.19
818	SLUG	C	LDS	1.289	0.37	2.73
819	SLUG	C	LDS	1.297	0.37	2.75
822	FHT	C	ALL	11.900	3.37	25.23
823	FHT	B&R	LDS	1.571	0.45	3.33

* Slug = Slug Test or "Rising Head Test," FHT = Falling Head Test.
** C = Cooper, et al., assumptions, B&R = Bouwer and Rice assumptions.
*** ALL = Alluvium, UDS = upper Denver sand; LDS = lower Denver sand.
† Bad test since water level was within gravel pack.

Table 2: Summary of Permeability Data, Basin A Neck Area, Rocky Mountain Arsenal.

Boring No.	Type of Test*	Analytical Method**	Aquifer Screened***	K (cm/sec) (x 10⁻⁴)	K (ft/day)	K (gal/day/ft²)
723	SLUG	C	UDS	9.850	2.79	20.88
723	SLUG	C	LDS	0.137	0.04	0.29
724	FHT	C	UDS	4.150	1.18	8.80
724	SLUG	C	LDS	19.500	5.53	41.13
725	FHT	C	ALL	1.600	0.45	3.39
725	SLUG	C	LDS	5.460	1.55	11.58
455	SLUG	C	UDS	12.150	3.44	25.76
455	SLUG	C	LDS	18.320	5.19	38.84
493	SLUG	C	UDS	22.430	6.36	47.56
493	SLUG	C	LDS	0.013	0.01	0.03
496†	SLUG	C	UDS	71.200	20.18	150.96
496	SLUG	C	LDS	19.360	5.49	41.05
801	SLUG	C	UDS	3.497	0.99	7.41
801	SLUG	C	LDS	7.238	2.05	15.35
802	SLUG	C	UDS	7.281	2.06	15.44
803	FHT	B&R	ALL	1.134	0.32	2.40
803	SLUG	C	UDS	11.530	3.27	24.45
803	SLUG	C	LDS	19.030	5.39	40.35
804	FHT	B&R	ALL	41.990	11.90	89.03
804	SLUG	C	LDS	7.232	2.05	15.33
806	SLUG	C	LDS	0.202	0.06	0.43
807	FHT	B&R	ALL	2.277	0.65	4.83
808	FHT	C	ALL	2.441	0.69	5.18
809	FHT	C	ALL	9.735	2.76	20.64
809	SLUG	C	LDS	6.766	1.92	14.35
810	FHT	C	ALL	5.986	1.70	12.69
812	FHT	B&R	ALL	0.438	0.12	0.93
812	SLUG	C	UDS	22.800	6.46	48.34
812	SLUG	C	LDS	21.320	6.04	45.20
814	SLUG	C	UDS	5.509	1.56	11.68
815	FHT	B&R	ALL	0.083	0.02	0.18
815	SLUG	C	UDS	3.866	1.10	8.20
816	SLUG	C	UDS	7.733	2.19	16.40
817	SLUG	C	LDS	3.495	0.99	7.41
818	SLUG	C	UDS	2.450	0.69	5.19
818	SLUG	C	LDS	1.289	0.37	2.73
819	SLUG	C	LDS	1.297	0.37	2.75
822	FHT	C	ALL	11.900	3.37	25.23
823	FHT	B&R	LDS	1.571	0.45	3.33

* Slug = Slug Test or "Rising Head Test," FHT = Falling Head Test.

** C = Cooper, et al., assumptions, B&R = Bouwer and Rice assumptions.

*** ALL = Alluvium, UDS = upper Denver sand; LDS = lower Denver sand.

† Bad test since water level was within gravel pack.

Table 3: Summary of Total Flux Determinations.

Section Line	Aquifer	Saturated Cross Sectional Area (ft^2)	Range of K (gpd/ft^2)	Range of i (ft/ft)	Flux (gpd)
F-F'	ALL	8,494	3.4*	0.014-0.020	504
F-F'	UDS	26,736	20,9*	0.016-0.026	12,096
F-F'	LDS	39,600	11,6-41.3	0.006-0.028	15,984
Y-Y'	ALL (West)	11,683	1019**	0.019-0.024	121,968
Y-Y'	ALL (North)	2,710	1019**	0.013-0.018	45,072
Y-Y'	UDS	134,580	5.1-25.8	0.010-0.020	30,096
Y-Y'	LDS	113,220	2.7-38.8	0.011-0.015	22,320
Z-Z'	ALL	6,140	1019**	0.005-0.020	45,072
Z-Z'	UDS	41,609	25.0-48.0	0.010-0.011	18,576
Z-Z'	LDS	65,075	10.0-40.0	0.004-0.011	17,280
9th Avenue	ALL	16,840	7000***	0.0006-0.001	70,704

* Only value available.
** Back-calculated value.
*** Pump Test value, Boring No. 368.

Table 4: Recommended Additional Well-Screen Emplacement, Basin A Neck Area.

Boring No.	Cross Section Line	Screen Length (ft)	Aquifer Screened	Bottom of Screen* Material Screened	(ft)
657**	F-F'	8	LDS	SM	94.0
655**	F-F'	8	LDS	SM	86.0
653	F-F'	8	SDS	SM	80.0
653	F-F'	4	ALL	SP	32.0
650	F-F'	4	ALL	SM	34.0
649	F-F'	4	ALL	SM	36.0
648	F-F'	4	ALL	SM	31.0
647	F-F'	4	UDS	SM	49.0
644***	F-F'	8	LDS	SM	121.0
139**	U-U'	12	UDS	SM	59.0
139	U-U'	12	LDS	SM	102.0
80**	U-U'	8	LDS	SM	108.0
723	V-V'/F-F'	8	UDS	SM	60.0
141**	V-V'	8	UDS	SM	60.0
141	V-V'	12	LDS	SM	97.0
675**	V-V'	8	UDS/LDS	SM	100.0
813	V-V'	12	LDS	SM	91.0
635**	V-V'/E-E'	12	LDS	SM	91.0
673	W-W'	8	ALL	SP	36.0
674**	W-W'	8	LDS	SM	78.0
674	W-W'	8	ALL/UDS	SP/ML	24.0
771	X-X'	8	LDS	SM	94.0
770	X-X'	24	UDS/LDS	SM	77.0
658	X-X'	8	UDS	SM	61.0
658	X-X'	12	LDS	SM	99.0
488**	X-X'	8	LDS	SM	75.0
42	X-X'	16	ALL/UDS	SP/SC	48.0

(Continued)

* All depths are from top of ground (TOG), MSL Datum.
** Redrill exploratory boring to 110 ft first to confirm screen interval.

Table 4: (Continued)

Boring No.	Cross Section Line	Screen Length (ft)	Aquifer Screened	Material Screened	Bottom of Screen* (ft)
617**	X-X'/E-E'	8	LDS	SM	70.0
876	Y-Y'	4	ALL	SP	42.0
876	Y-Y'	8	UDS	SM	69.0
491***	Y-Y'	12	LDS	SM	124.0
490***	Y-Y'	12	LDS	SM	110.0
822	Y-Y'	12	LDS	SM	119.0
130***	Z-Z'	12	LDS	SM	122.0
492***	Z-Z'	12	LDS	SM	103.0
492†	Z-Z'	12	UDS	SM	78.0
492	Z-Z'	8	ALL	SM/SP	37.0
776	F_1-F_1'	16	UDS	SM	43.5
776	F_1-F_1'	8	LDS	SM	91.0
774	F_1-F_1'	8	LDS	SM	63.0
772	F_1-F_1'	8	ALL	SM/SP	39.0
770**	F_1-F_1'	12	LDS	SM	76.0
771	F_2-F_2'	8	LDS	SM	70.0
773	F_2-F_2'	4	ALL	SP	48.0
773	F_2-F_2'	8	LDS	SM	68.0
775	F_2-F_2'	8	LDS	SM	70.0
732	G-G'	4	UDS	SM	36.0
726†	G-G'	8	ALL	SM	41.0
726	G-G'	8	LDS	SM	88.0
734	G-G'	8	LDS	SM	88.0

* All depths are from top of ground (TOG), MSL Datum.
** Redrill exploratory boring to 110 ft first to confirm screen interval.
*** Redrill exploratory boring to 130 ft first to confirm screen interval.
† No trap should be used.

Table 5. Recommended New Exploratory Borings, Basin A Neck Area.

Boring No.	Section	Northing	Easting	Depth (ft)	Probable No. of Screens
X-1	25	190,610	2,186,290	130	2
X-2	25	190,480	2,185,610	130	2
X-3	25	190,450	2,184,910	130	2
X-4	25	190,330	2,187,210	130	2
X-5	25	189,800	2,185,730	130	2
X-6	25	189,790	2,184,900	130	2
X-7	25	189,610	2,186,900	130	2
X-8	25	188,660	2,187,200	130	2
X-9	25	188,700	2,185,880	130	2
X-10	25	188,860	2,184,900	130	2
X-11	25	189,370	2,183,670	100	2
X-12	25	188,580	2,183,670	100	2
X-13	25	187,950	2,187,450	100	2
X-14	25	187,860	2,186,100	130	2
X-15	25	187,050	2,187,520	100	2
X-16	25	187,040	2,186,230	130	2
X-17	25	186,350	2,186,350	130	2
X-18	25	186,580	2,185,060	130	2
X-19	25	187,210	2,184,550	130	2
X-20	25	187,280	2,183,660	110	2
X-21	25	186,520	2,183,720	110	2
X-22	26	189,740	2,183,090	100	2
X-23	26	189,720	2,182,390	100	2
X-24	26	189,260	2,182,700	100	2
X-25	26	188,600	2,182,720	110	2
X-26	26	187,540	2,182,640	130	3
X-27	26	188,050	2,182,290	110	3
X-28	26	187,580	2,181,390	110	2
X-29	26	186,840	2,181,950	130	3

Table 5: (Continued)

Boring No.	Section	Northing	Easting	Depth (ft)	Probable No. of Screens
X-30	26	186,950	2,181,130	110	2
X-31	26	186,480	2,181,550	110	2
X-32	26	187,750	2,180,490	110	3
X-33	26	186,610	2,180,630	110	3
X-34	26	186,580	2,180,050	110	3
X-35	26	187,040	2,180,060	110	3
X-36	26	188,560	2,179,470	110	2
X-37	26	187,960	2,179,360	110	2
X-38	26	188,980	2,178,380	110	2
X-39	26	187,790	2,178,750	110	2
X-40	26	186,770	2,179,140	110	2
X-41	26	187,660	2,178,000	110	2
X-42	26	186,080	2,177,370	110	3
X-43	26	185,940	2,181,370	110	3
X-44	26	185,450	2,181,200	110	3
X-45	26	185,070	2,181,400	110	3
X-46	26	184,460	2,180,320	130	3
X-47	35	184,060	2,181,580	130	3
X-48	26	189,190	2,179,000	110	2

Table 6: Well Screens Recommended for Drilling Out and Grouting Up.

Well No.	Section	Aquifer Screened	Trap Bottom (ft)	Screen Bottom (ft)	Depth Drilled (ft)
438	26	ALL	80.0	41.9	80.0
455	26	ALL	89.4	41.1	89.4
461	26	ALL	81.4	47.4	81.4
405	26	ALL	90.0	47.0	90.0
419	26	ALL	89.8	47.5	89.9
423	26	UDS	61.5	59.6	74.0
880* (ESA)	26	UDS	60.0	55.0	60.0

* Boring on Skimmer Pond Weir, southeast corner Basin F. Well screen never properly installed or backfilled. If possible pipe should be removed, hole redrilled open, screen reset with interval at 45.0-55.0, and proper grouting procedures followed. Gravel pack no shallower than 40.0 ft.